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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD REPORT 814

Integrated Airframe Design Technology

(les Technologies de la conception intégrée des cellules)

Papers presented at the 82nd Meeting of the AGARD Structures and Materials Panel, held in Sesimbra, Portugal, 8-9 May 1996.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization

Organisation du Traité de l'Atlantique Nord

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— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

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Integrated Airframe Design Technology

(AGARD R-814)

Executive Summary

In order to achieve economically viable high-performance aircraft of the future, an Integrated Airframe Design (IAD) process is required. Integrated airframe design embraces the concept of bringing together all of the aspects of airframe design, including various disciplines such as structures, materials, aerodynamics, propulsion, systems, controls and manufacturing from conceptual design all the way through to the final product and its repair and maintenance. It also includes the subdisciplines which are involved in each discipline and the interactions these have with one another. Moreover, an IAD process also affects organisational structure of personnel. Typically, many organisational units are involved in the design process. An IAD approach increases the interaction between these organisations as well as changes the way they interact with one another. In contrast, the conventional design process is basically sequential or hierarchic in nature and is broken down into many steps which are loosely coupled to one another (i.e., there are few iterations between design steps and limited interaction between organisational units). Moreover, the organisational structure is typically set up to mimic the conventional design process so it too is sequential. An IAD process would be radically different from the conventional design process. It would permit many disciplines to operate in parallel thereby reducing design cycle time and overall costs.

The results of this AGARD Workshop on Integrated Airframe Design emphasized that the recent and future advances in high-performance computer hardware and software systems provide the opportunity to create a process that will allow the process steps and disciplines to rapidly interact with one another. Moreover, comprehensive data bases will provide organisational units access to one anothers data and models, thereby promoting more interaction between organisations and moving toward a concurrent engineering environment for airframe design. Co-location of personnel with different discipline background will be required, however, this may take the form of "virtual co-location" brought about by high-speed computer networking and audio-visual aids. This will make it possible to create a more concurrent aircraft design process and consequently, shorten the design and manufacture process and improve quality.

Les technologies de la conception intégrée des cellules
(AGARD R-814)

Synthèse

La réalisation d'aéronefs à hautes performances dans des conditions économiques viables à l'avenir passe par l'adoption d'un procédé de conception intégré (PCI) en ce qui concerne les cellules. La conception intégrée des cellules réunit en un seul concept l'ensemble des aspects de la conception des cellules, y compris les différentes disciplines telles que les structures, les matériaux, l'aérodynamique, la propulsion, les systèmes, les commandes et la fabrication, du stade conceptuel de l'étude jusqu'au produit final, y compris la maintenance et les réparations. Elle comprend également les sous-disciplines et leurs interactions. En outre, la mise en application d'un procédé PCI n'est pas sans conséquences pour la structure hiérarchique du personnel. En règle générale, de multiples unités fonctionnelles sont appelées à intervenir dans le procédé de conception. L'adoption d'une approche PCI a pour effet d'intensifier l'interaction entre ces unités tout en modifiant la nature de cette interaction. En revanche, le procédé de conception classique est essentiellement séquentiel ou hiérarchique, étant décomposé en un certain nombre d'étapes plus ou moins liées (c'est-à-dire qu'il y a très peu d'itérations entre les étapes de conception et que l'interaction entre les unités fonctionnelles est très limitée). En plus, étant donné que la structure hiérarchique est normalement établie de façon à imiter le procédé classique, elle est séquentielle aussi. Un procédé PCI serait radicalement différent d'un procédé de conception conventionnel. Il permettrait l'exploitation de plusieurs disciplines à la fois, réduisant ainsi la durée du cycle de conception et les coûts globaux.

Cet atelier AGARD sur la conception intégrée des cellules a conclu que les progrès récents et futurs dans le domaine des systèmes informatiques à hautes performances permettront de créer un procédé basé sur l'interaction rapide entre les étapes et les différentes disciplines. En outre, des bases de données très complètes permettront aux unités fonctionnelles d'avoir accès aux autres données et modèles, encourageant ainsi l'interaction entre les organisations, dans un environnement conceptuel concomitant pour la conception des cellules. Le regroupement sur un même site de personnels de différents disciplines sera nécessaire. Elle pourrait aussi être réalisé virtuellement, par un au travail en réseau informatique à grande vitesse et des aides audio-visuelles. Ces mesures permettront la création d'un procédé de conception aéronautique plus concourant, ayant pour effet de raccourcir le procédé global de conception et de fabrication et d'en améliorer la qualité.

Contents

Preface

In recent years it has become more apparent that all the disciplines

Structural Optimization

Integrated Design

Concurrent Engineering

Virtual Manufacturing

have very close ties and relations.

All the efforts made are directed at reducing life cycle cost and hence making weapon systems more affordable. Integrated Airframe Design Technology is an important element of a number of activities required to improve the business performance of aircraft companies worldwide. The customers require more reliable products at an affordable price that perform to specification and are easy to support in service.

The time required to design and build an aircraft needs to be reduced and an environment created whereby all parties involved can work together to influence the development of the design at an early stage. This approach coupled with enhanced visualisation and simulation of both the functional and physical elements of the product design will enable modifications to be implemented as part of the design process before the start of manufacturing/build. Thus the need for changes to be carried out during and after production build will be significantly reduced and will result in impressive savings in cost.

Integrated Airframe Design Technology provides the basis for this new environment to be developed.

The Workshop was organised as a follow up to the initial event which took place in Antalya, Turkey on April 19th and 20th 1993.

The objective was to evaluate the status of technology development within the major aerospace companies together with an assessment of the research being carried out by the academic community.

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TECHNICAL EVALUATION REPORT

Integrated Airframe Design Technology

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Technical Evaluation - Integrated Airframe Design Technology

1. Introduction

Integrated Airframe Design Technology is an important element of a number of activities required to improve the business performance of Aircraft companies worldwide.

The customers require more reliable products at an affordable price that perform to specification and are easy to support in service.

The time required to design and build an aircraft needs to be reduced also an environment created whereby all parties involved can work together to influence the development of the design at an early stage.

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Integrated Airframe Design Technology provides the basis for this new environment to be developed.

2. Workshop Theme

The theme of the workshop was on the technology required for integration of the airframe design process coupled with the need to re-organise the business into a series of multi-disciplined teams operating in a concurrent engineering environment focused on project deliverables.

3. Purpose and Scope

The workshop was organised as a follow up to the initial event which took place in Antalya, Turkey on April 19th and 20th 1993.

The objective was to evaluate the status of technology development within the major aerospace companies together with an assessment of the research being carried out by the academic community.

From this review of current activities the technology was then required to be projected forward into the next decade and beyond identifying areas which need to be concentrated on for future research and development.

4. Technical Evaluation

A total of 15 papers were presented spanning 3 sessions over a 2 day period. The majority of papers concentrated on industrial status and were presented by engineers who had responsibility for implementing the technology in a business environment.

The trend was distinctly advanced since the last session in Antalya in that companies then were talking about creating digital models of the design whereas the theme in Portugal was very much concentrated on how to use the digital models in manufacturing for planning, tooling and product assembly. Also there was a notable acceptance of Concurrent Engineering being the normal way of business rather than something new.

All of this represents a very big change in that in a relatively short period of time organisations have been dramatically re-shaped and a major step forward has been taken in the migration from a paper based aircraft design and qualification process to an electronic platform.

Companies involved in reviewing their industrial status were:-

- Northrop-Grumman
- Lockheed-Martin - Fort Worth
- DASA
- British Aerospace
- Fokker represented by FAIR Information Services
- Aerospatiale/Airbus
- Dassault Aviation
- Rockwell
- CASA
- Alenia

All companies emphasised the importance of integration and much visible progress has been made from the 'Islands of Automation'. The boundaries are still an area for debate and there was a strong view that beyond the initial need to use common geometry in all areas the law of diminishing returns comes into play. Thus business justification

needs to be applied to achieve some sensible guidelines for integration of each element of the design process.

Data Management and exchange was viewed as essential. STEP discussed as the formal data archive standard to take account of product life being longer than the current systems being used for design.

Most companies have taken up the challenge of physical simulation via digital geometry models. Traditional computerised Structural and Aerodynamic methods appeared to be in everyday use by all the presenters.

Taking more specific account of the papers presented Dr. Dianne Wiley from Northrop Grumman (ref 1.) gave a very convincing account of design for affordability with emphasis on the manufacturing interface and the cost savings that can be achieved by integrating the process from product design through to tooling and manufacturing.

A number of important points were raised which show how the technology is developing from creation of the solid model to utilization of the data via the use of features, attributes, associativity and parametrics which have the potential for providing significant business benefit from application to the manufacturing process.

In addition linking into factory simulation modelling sets the scene for a major customer requirement for surge manufacturing particularly for spares acquisition whereby electronic ordering can be linked directly into the automated processes in the manufacturing operation to provide rapid response for fast delivery to the customer.

This presentation provided a good lead in for Jack Ellis from Lockheed-Martin (Ref 2) who concentrated on the design process from the conceptual stage and its stakeholders through to the digital mock-up and the use of interference and tolerance analysis tools to quality assure the assembly operation.

A key point here was the recognition of treating integrated design as a 'culture' in which the necessity of interaction is recognized by all the participants. The requirements usually originate within the design function but with the advent of Integrated Product Teams design may not always take the lead. In this culture all members of the team work together, interactively, until all the design requirements are satisfied. There is no 'transom engineering' in which data is passed without consideration for interaction or feedback.

Development of the loads model together with visualisation of external and internal loads was seen as a critical element of the process because the final design can only be as good as the quality of the loads. Use of higher level codes such as Navier-Stokes for situations such as separation and shock-boundary layer interaction is also necessary to provide or improve this quality.

This led to a further point on structural sensitivities being particularly important in terms of identifying critical areas for testing and providing the opportunity to reduce testing as more confidence develops in analysis results.

The need for a common architectural framework for the design to enable simultaneous considerations of design requirements was raised by Dr. Kramer (ref 3) from Daimler Benz Aerospace.

50% to 80% of design time is spent organising and moving data between applications. Thus the adoption of an integration platform and effective Product Data Management will have a significant effect on reducing design cycle times and overall costs. In addition there needs to be provisions and rules for release of preliminary information and/or incomplete data to foster teamwork and communication so that teams can truly work in parallel without waiting for the data to be 'perfect'.

STEP was also referred to here as the standard for data storage in a neutral format and as an aid to data translation between systems although it is a fact that the practical application of STEP has a long way to go before its true value can have any business impact.

Dave Thompson from British Aerospace (ref 4) concentrated on the 'Integrated Airframe Design' environment centred on structural optimisation and the importance of establishing a compatible hardware/software environment together with common data representation being essential to provide a suitable platform for further development of multidisciplinary optimisation.

This strengthened the case as presented by Dr. Krammer (ref 3) for an architectural framework that allows 'plug and play' of specialist tools utilizing common geometry for all processes.

The Fokker Aircraft presentations provided by D. J. Laan (ref 5) came the closest to describing all the elements of 'Integrated Airframe Design'. It also raised the issue of integration relevant to both functional and physical simulation. This bringing together of the 'Systems Engineering' and 'Airframe' environments will be absolutely essential for the future as the complexity of the products continues to evolve. He also pointed out the difference between the 'top down' approach to MDO (considering system requirements, analysis, functionality, architecture, verification and validation) and the 'bottom up' approach (eximplified by the global sensitivity equation method of coupling analysis models and technical disciplines). It was emphasized that a blending of these approaches was necessary to achieve a successful implementation of the MDO approach to integrated design.

Mr. A. Carcasses from Aerospatiale (ref 6) gave an account of the AIRBUS Industries approach to integrated engineering which is critical because of the diverse locations of design teams in different European countries.

This presentation also brought out the importance of business decisions on 'make or buy' relevant to

manufacturing being critical to achievement of benefits from the integrated process. A change of manufacturer during the production phase to a 'non compatible supplier' could completely negate the business benefits achievable from investment in the overall process.

Product Data Management also came out as the key to data control for the whole global approach to design and build of the product.

Christian Petiau from Dassault Aviation (ref 7) gave a very informed technical insight into the important relationships between design, analysis, flight and static testing. This paper also pointed out a major deficiency which exists in current finite-element based structural optimization and sizing systems which is the inability to go from average element sizes (such as skin gauge) to the actual part drawings. Currently this is a manual/semi-automated process involving re-definition of geometry but could be automated with the suitable development of appropriate expert systems capturing the experience of the structural designers. There are also deficiencies in the analytical determination of allowables eg. strength, material properties, etc. therefore these are still primarily determined by test. Further work is required into the analysis of failure mechanisms.

The importance of recording history was stressed as an automatic process to enable iterative replays of the design and to make it easier to modify complex models. This is a critical area in terms of quality assurance and as the technology develops will be an essential element of the design audit and qualification process.

The Rockwell International industrial status presented by S. K. Dobbs (ref 8) emphasised how cost analysis could be integrated into the design process and was the only presentation to introduce the concept of life cycle costing into the Multidisciplinary Optimisation process. He also emphasized the introduction of additional disciplines such as structural optimization into the conceptual phase of design to improve the leverage on cost of early design decisions with improved knowledge of the end product.

Cost sensitivities were discussed and it was generally agreed that accurate data is difficult to pull together. This approach to MDO coupled with the Lockheed/Martin, Northrop/Grumman and Fokker presentations form a good future overview of 'Integrated Airframe Design'.

Several presentations referred to different approaches to Multidisciplinary design optimisation as per the CASA paper presented by M. A. Morell Fuentes (ref 9) which used analytical stress models of components rather than basic finite elements to perform a design optimization where key parameters of the components formed the design variables. While this approach is very limited compared with large FEM models it might provide a usable tool for groups working in a design environment with limited resources or in the early stages of a design study. However designs arising from this method would have to be subjected to full analysis and

test for safety and certification purposes.

The Monte Carlo -based stochastic finite element method (ref 11) as presented by Dr. J. Vantomme from the Royal Military Academy - Brussels showed large variations of properties of composite structural components and used a statistical method to account for these uncertainties. Generally these large variations are not observed when built up structural components are tested however the method did illustrate potential for resolving non-linear situations.

Global/Local analysis in finite element technology presented by N. Gaultieri from Alenia (Ref 14) described the conventional application of substructuring to the design and verification of complex structures.

The theory of topology optimisation of 3D linear elastic structures (ref 15) was presented by P. R. Fernandes. Topology optimization is an area of increasing interest which could be an important tool in integrated design but is still in the earliest stages of application especially in the Aerospace industry. However, interesting applications have been presented in other fields such as civil engineering (bridge design) electric power transmission and automotive design. This is an area which should receive more attention in Aerospace.

An interesting discussion developed around the paper presented by Prof. Dr. J. M. G. Conca (ref 13) from INTA Madrid which concentrated on the understanding of error both in the theory and computational analysis. This is an important area of research if progress is to be made towards reducing the amount of physical testing required and perhaps more importantly gaining the acceptance for aircraft qualification via computational analyses.

Major N. P. Ribeiro from the Portuguese Airforce Aeromedical Centre presented an interesting diversion into medical science and the human limitations in flight (ref 10) drawing attention to the case for ergonomics to be taken into account on the optimised design with study concentrating on how to reduce human error by the application of good design methodology.

Finally the Gas Turbine Engine conceptual design process was reviewed by M. Stricker from the Wright Laboratory (ref 12).

This brought out the importance of bringing together the engine and aircraft designer early in the concept phase. Innovative aircraft designs can be strongly influenced at the embryonic stage by propulsion constraints. Thus the need to bring the supply chain into the design process via virtual co-location and closely integrated multi-disciplined teams being an ideal environment to target for the future.

5. <u>Conclusion</u>

It is perhaps useful here to mention some of the areas not covered during what was a very comprehensive workshop on Integrated Airframe Design.

- Multi disciplinary optimisation beyond the

range of aerolasticity taking into account product performance and on a wider basis reliability, maintainability and of course as raised by Rockwell, costs.

- Importance of the people problems and need for more intensive training as product complexity increases and the systems user base expands.

- Integration of functional and physical simulations through products such as MATLAB/SIMULINK and MATRIX 'X' although this was briefly mentioned by Fokker.

- Feature based modelling and parametrics, concentrating on the need to record design history to improve quality assurance and the problem of how to change a complex parametric design model.

- Customer and Pilot viewpoints. How can we move faster to resolve problems and how can we help the pilots to get to grips with the complexity of the systems which are becoming more and more automated.

- The need to reduce or eliminate testing and how to qualify the product in an analysis environment. Do we need to understand sensitivities better and test only critical areas?

In summary the problem domain can be divided into the following broad categories:-

- Global - Covering fully integrated systems inclusive of customers, partners, suppliers, etc

- Local - Many disciplines at a high level of analytical detail at a company level. How is this going to fit together? The paper from Fokker came closest to addressing this.

- Sub-Local - Multi-disciplinary optimisation linking across disciplines with new mthods and emphasis on the specialist analysis required.

Leading on from these points it is appropriate to briefly consider where we are going and what will the world be like in the year 2020. Some views on this future scenario are offered here:

- Synchronised Airframe/Systems technology life cycles will be integrated with

Production/Manufacturing and customer Support.

- Customers will access digital models for maintenance and will order spares by initiating an electronic order from the model.

- Rapid response to the electronic orders will be achieved by closely integrated models capable of driving the production line into producing the final article.

- Integrated product data bases with effective data management will be linked to configuration control systems to provide effective control of the fleet covering both software and hardware.

- A CALS (Continuous Acquisition and Lifecycle Support) competitive environment linked to Suppliers, Partners and Customers via EDI thus the vision of global commerce will be reality.

- Post Design Service Data Bases will be established shared with the customer with joint or supplier support of the product being much more the order of the day.

- Multidisciplinary optimisation will have been achieved inclusive of the current traditional activities coupled with life cycle costing, reliability and maintainability, manufacturing and customer requirements.

- High performance computing will be in everyday use for analysis and optimisation on the desk top linked to virtual networks of almost limitless power.

- Rapid prototyping for Airframe components and Airborne software complete with automated generation of code from requirements specifications.

- Analysis will have largely replaced testing for the qualification process although limited testing will still be required for critical elements of the design.

- Multi Media and enabling technology will be in everyday use facilitating virtual co-location and telecommuting.

All this will be part of an electronic environment supporting the total business linked into a global electronic network supporting business worldwide.

All the above will need investment and buy in from Senior Management to make it happen and the 'winners' will be the companies who are most prepared to pioneer the technology.

In addition people/organisations will have to evolve with the Technology and this is a major issue for the future.

6. Recommendations

A further workshop is recommended to follow up the status through to the next stage. This needs to include disciplines from other areas particularly Aerodynamics, Flight Controls, Systems Engineering, Manufacturing and the Customer Support areas.

Also an update on the future directions of 'Information Technology' is recommended as per the paper presented at the Antalya conference by A. K. Noor and J. M. Housner (ref 16).

Research and development for the future needs to concentrate on the next generation of hardware and software together with effective utilization of optical computing, smart cards and chips, bar coding, access control, part effectivity implemented as an integral part of the aircraft structure.

Feature based modelling, associativity, parametrics and variation simulation analysis will need to be developed as an integrated process to implement more effective assembly and improve the quality of the design.

Metrics need to be developed to understand better how process improvements and enabling technology are delivering benefits. This will greatly improve investment flows if it can be achieved.

The whole topic of life cycle costs and its integration into the optimisation process needs to be further developed.

Error rates need to be much more clearly understood if we are to progress towards analysis as a qualification route.

Emphasis in future sessions also needs to concentrate on the vision of the future to provide a better focus for future directions.

Finally as already mentioned the main problem of integration revolves around people and organisation.

How do we make this fit with a fast changing business environment and still deliver products the customers can afford to buy.

A. L. Shaw/C. J. Borland.

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Integrated Airframe Design Technology at Northrop Grumman

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Design for affordability is the new paradigm for the 21st Century. Balancing the conflicting goals of systems superiority and systems affordability is the challenge of multidisciplinary design optimization on a larger scale than has ever been done before. Addressing the realities of the future aerostructures business has led to a new vocabulary.

Northrop Grumman pioneered many of these concepts on the B-2 Program during the 1980's. Since then we have taken the lessons learned, coupled with commercial off the shelf software and integrated them into formal protocols for affordable aircraft production, resulting in a Toolbox for Affordable Production.

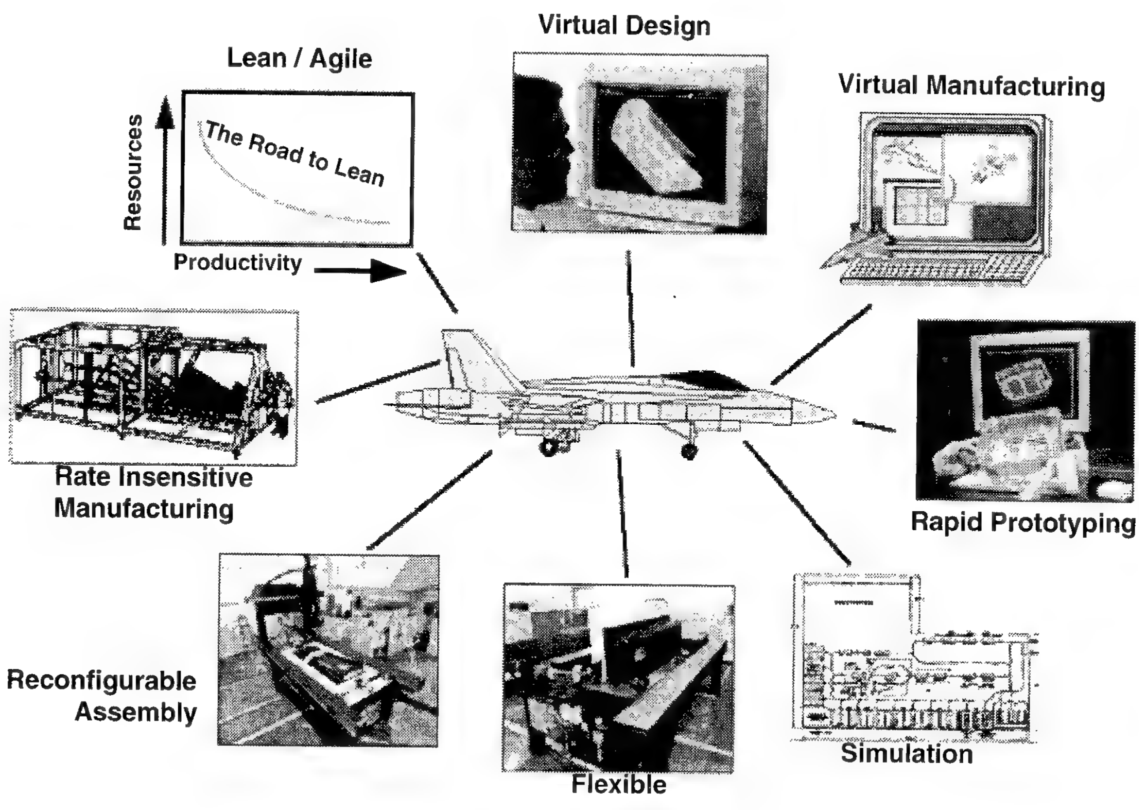


Figure 1 - A New Vocabulary for Affordability

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

Toolbox for Affordable Production

- Integrated Product/Process Teams (IPPT)
- Common Electronic Database
- Virtual Manufacturing
- Computer Aided Design/Engineering
- Multidisciplinary Design Optimization
- Variation Simulation Analysis
- Automated Tooling Design
- Simulation/Process Modeling
- Rapid Prototyping
- Reconfigurable Tooling
- Automated Process Management

Key enablers for Affordable Production are Integrated Product and Process Development Teams, the Common Electronic Database and Virtual Colocation. The IPPT environment assures design for affordability by replacing the old vertical organizational structures with cultural changes to business practices, physical organization, and technology tools.

It facilitates design for manufacturing by inviting the shop into the design process and the design team onto the factory floor. It minimizes change by requiring early buy-in from down-stream functions.

Another key process for affordability is virtual colocation. This concept allows us to reduce facility costs by linking multiple production sites together to achieve a seamless production line. First pioneered on the B-2 program, virtual colocation has been transitioned to our Commercial Aircaft Division as a best practice.

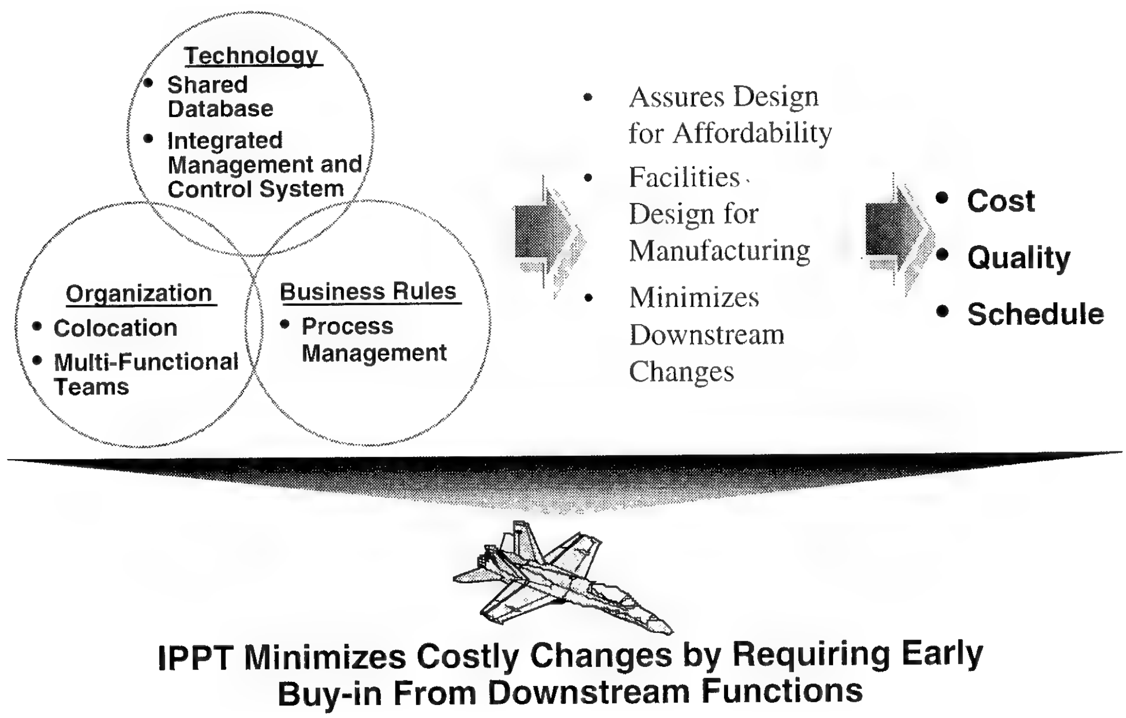


Figure 2 - IPPT Facilitates Affordable Production

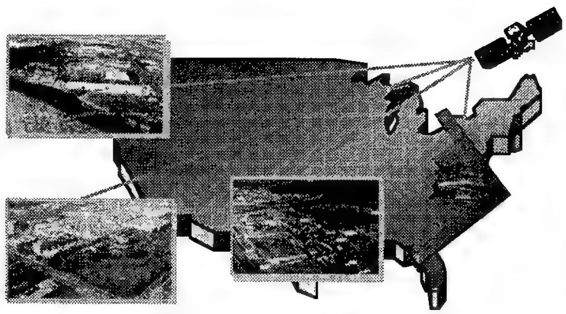


Figure 3 - Virtual Colocation is a Key Enabler of Virtual Manufacturing.

The Common Electronic Database is the critical enabling process for virtual manufacturing. By allowing people to work concurrently on different tasks or different phases of the production process, it reduces design/change cycle time and process variability, encourages process commonality and facilitates just in time procurement. We have shown that the use of the common 3-D electronic design database within an IPPD environment for design, analysis, manufacturing planning, tooling, fabrication, assembly and tech orders eliminates as many as seven layers of interpretation and potential for variability between the designer and the final hardware product.

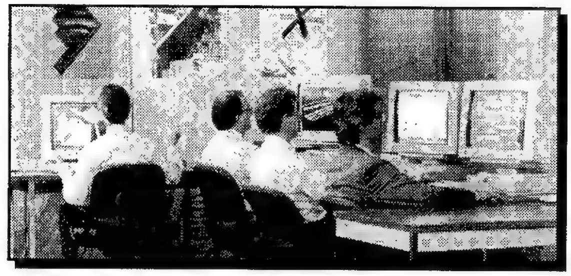


Figure 4 - Common Electronic Database Allows Concurrent Work on Multiple Tasks or Phases of Production Which Can Be Geographically Separated.

Virtual manufacturing (VM) is the organizing principle of our production process. VM is a simulated environment in which we can live the production process end to end prior to commiting to design, hardware and expensive facilities and capital asset costs.

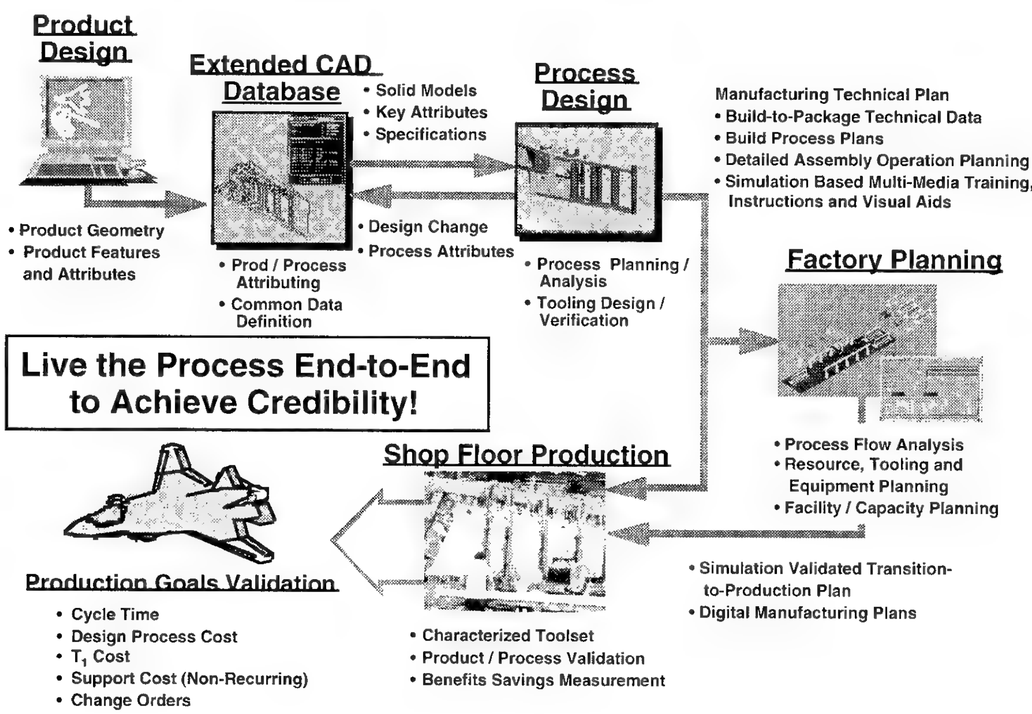


Figure 5 - Virtual Manufacturing

It allows us to validate our production goals of

- Reduced Cycle Time
- Reduced Design and Manufacturing Cost
- Reduced Support Costs
- Reduced Part Count
- Reduced Floor Space
- Reduced Change Activity
- and Improved Assembly Fit Up and Quality!

VM allows us to lower our entry point on the learning curve by simulated learning.

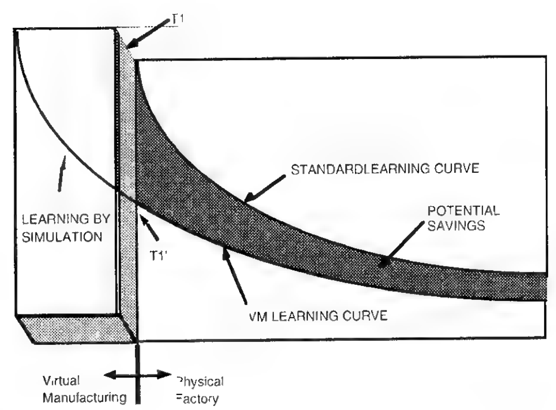


Figure 6 - VM Lowers Production Learning Curve

Computer aided design and engineering (CAD/CAE) systems are the backbone of VM, as they give the earliest expression of a new product design. The critical enabling capability of CAD is feature based modeling and associativity--that is the ability to initiate a design change and have it concurrently propagate through all levels of the database. In response to a technology void in the early 1980's, Northrop Grumman built our own CAD systems and data management protocols. The accelerated evolution of commercial CAD capabilities, shown in Figure 7 has been in direct response to customer pull.

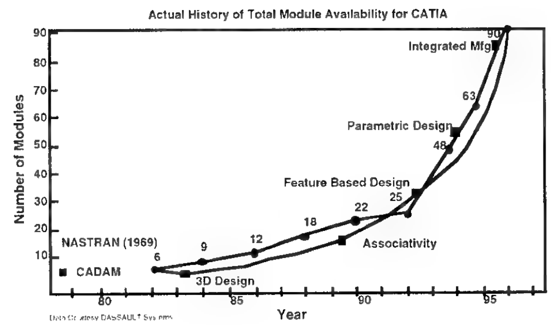


Figure 7 - Rapid Evolution of CAD Capabilities Enables VM Environment

Coupled to CAD is the ability to rapidly optimize a structure for structural efficiency. The ASTROS Multidisciplinary Optimization Code is a commercially available code, developed under contract to Wright Laboratories, which allows us to insure the structural integrity of a component subject to an array of concurrent constraints.

ASTROS was recently utilized to perform a weight optimization of a pre-production baseline design of a vertical stabilizer. This exercise, which addressed eleven concurrent structural constraints, resulted in a 6% weight savings and was accomplished in only two calendar months. It validated the accuracy of the ASTROS tool to capture both the technical knowledge and intuition of an experienced design team.

Design for Manufacturing is a key goal of Concurrent Engineering. One analysis tool which encourages communication between Design and Manufacturing is Variation Simulation Analysis. Using the commercial VSA(R) software, we can predict, control and

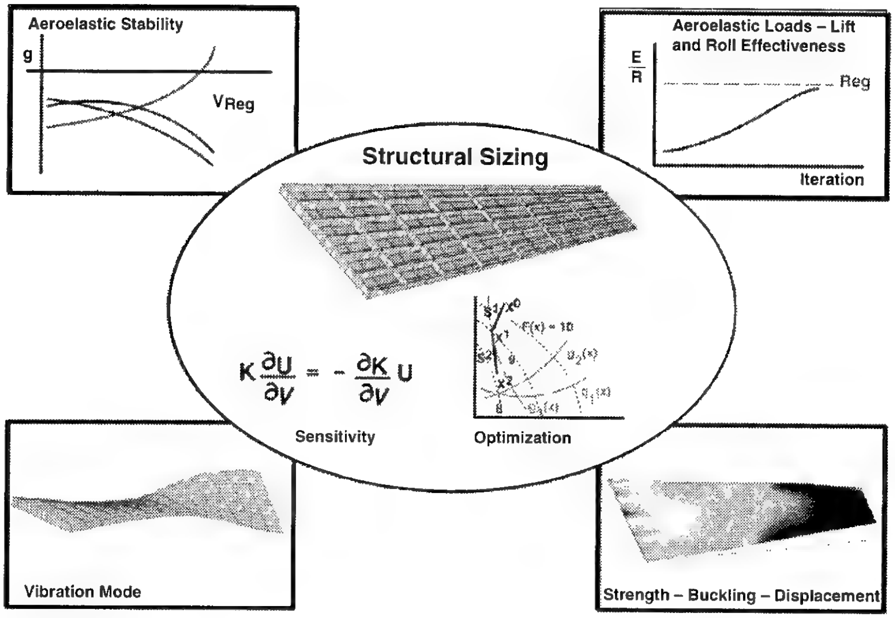


Figure 8 - ASTROS Multidisciplinary Design Optimization Code Considers Simultaneous Constraints.

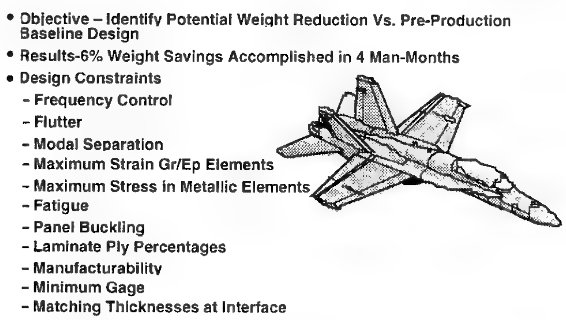


Figure 9 - Typical ASTROS Optimization of Vertical Stabilizer

reduce assembly variation during design of a product before it is built. VSA® eliminates design and process incompatibility and allows comparative analysis between designs. By evaluating Statistical Process Control (SPC) data, it identifies both the location and percent contribution of each variation in an assembly, so that focused correction of design deficiencies can be accomplished. Consider the following example of how VSA® and SPC can help the design process. Pareto analysis of the number of occurrences of each assembly operation in Figure 10 shows that drilling and fastening are the dominant assembly operations. Examination of a set of aircraft production drawings found 35 different hole callouts for a 3/16 inch fastener--that is 35 unique processes that a mechanic must be responsible for performing correctly. This VSA® exercise

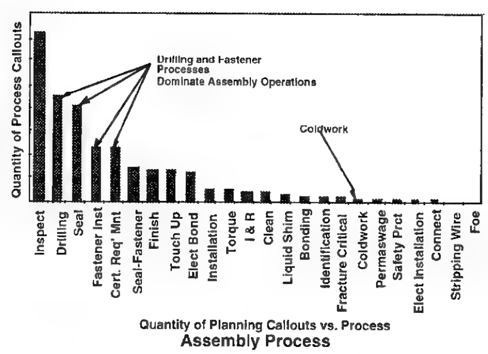
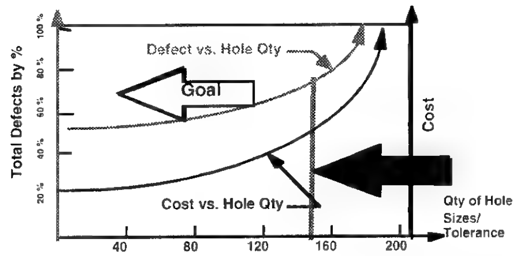


Figure 10 - Drilling and Fastening Dominate Assembly Operations.

showed that for future programs, the way to reduce manufacturing costs and defects is to limit the number of hole size/tolerance callouts allowed in the product design.



Reducing Quantity of Hole Sizes and Tolerances Will Reduce Defect Counts and Support Labor Requirements

Figure 11 - Cost Impact by Quantity of Hole Sizes and Hole Defects.

A large portion of production costs lies in the risk and expense of production tooling. The ability to derive production tooling directly from the CAD database was demonstrated on the B-2. An integrated methodology for rapid tool concept selection was developed under the Advanced Tooling Manufacture for Composite Structures (ATMCS) program, sponsored by Wright Laboratories. We have shown that use of the ATMCS software for typical composite structure tools enables a 98% savings in tool design compared to conventional design processes.

Tool Type	CAD Conventional	CAD ATMCS	Time Savings	% Savings
Trim and Drill Fixture	16.0 hour	13.7 min	15.7 hour	98.6 %
Eggcrate Tool	8.0 hour	18.7 min	7.7 hour	98.6 %
Billet Tool	8.0 hour	22.3 min	7.6 hour	98.6 %
Master Model	6.5 hour	16.5 min	6.2 hour	98.6 %
Ply Locator	3.0 hour	7.4 min	2.9 hour	98.6 %

Figure 12 - Demonstrated Tool Design Time Savings using ATMCS Software

Continuing this example for fabrication of an eggcrate tool, the ATMCS design allowed elimination of intermediate processes which could introduce variances and tolerance errors and led to greater than 60% savings in tool fabrication.

Eggcrate	Hand-Cut	Waterjet	Savings	
			Hours	%
Large	105.4	37.1	68.3	65%
Average	61.8	21.5	40.3	65%
Small	36.8	10.2	26.6	72%

Notes: Times Include Assembly of Back-Up Structure
Savings Are Attributable to Standardized Output of ATMCS Macro and Utilization of Water-Jet Technology

Figure 13 - ATMCS Design Saves Tool Fabrication Time Also.

Simulation is another CAD-driven virtual manufacturing process which offers cost reductions. Factory Simulations allow optimization of factory layouts prior to commiting capital assets. A recent simulation of a missile coating facility using the Automod® software showed that the factory plan as originally designed would not support production schedules. The monorail for moving work between stations was inadequate and bottlenecks occurred early in the coating process. Use of Automod® to optimize the factory plan allowed a trade study of a number of different manufacturing processes (spraying versus bonding, sequential versus batch processing, and single product versus mixed product processing.)

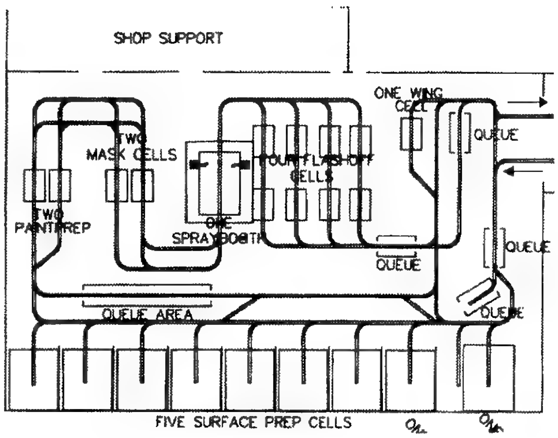


Figure 14 - Factory Layout Simulation Optimized by Automod® Software.

Sequential processing of a mixed product line resulted in a reduction of part cycle time by two days, reduced work in process by 56%, and resolved initial bottlenecks. This simulation result was especially valuable, because the optimized solution is counterintuitive--batch processing turned out to increase cycle time, increase work in process and increase facility size.

Transitioning from the Virtual Manufacturing environment to hardware, there are a number of processes which facilitate production affordability. Rapid prototyping allows fit, form, function checks prior to commiting design to hardware. Rapid prototypes can also be used for low cost tool masters. Figure 15 shows how a rapid prototype is developed from the CAD model. The process called Laminated Object Manufacturing was used to create a full size low cost prototype of a weapons dispenser strongback, approximately 18 inches x 42 inches in size, for use as the tool master.

Reconfigurable and flexible tooling is being used at Northrop Grumman on both military and commercial programs. We have shown the cost benefits and rate insensitivity of reconfigurable production systems where production mix may change any time during the production run and the typical "lot size" is one.

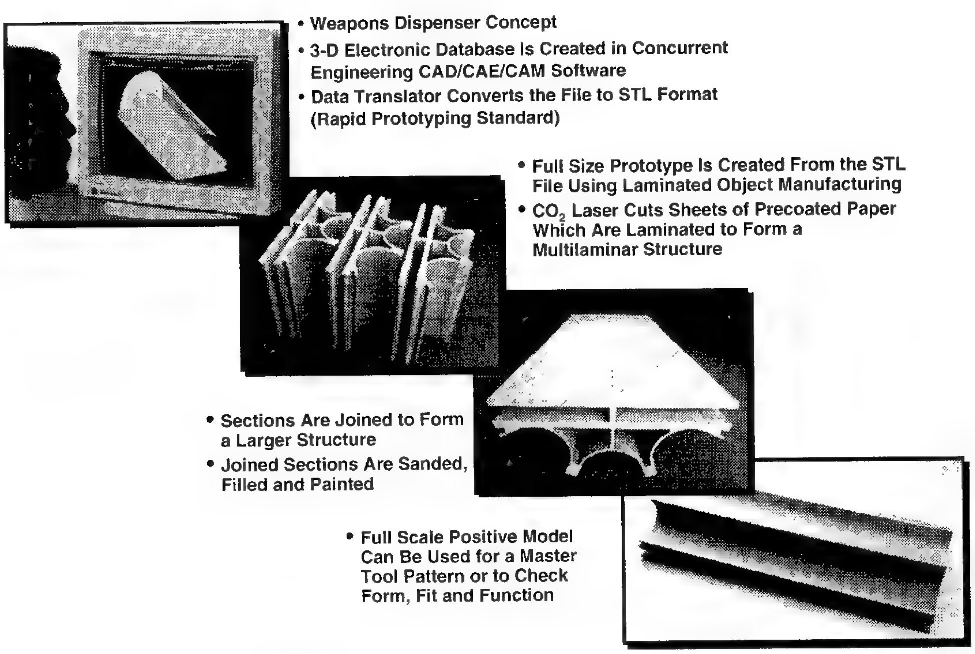


Figure 15 - Rapid Prototyping --From Concept to Hardware.

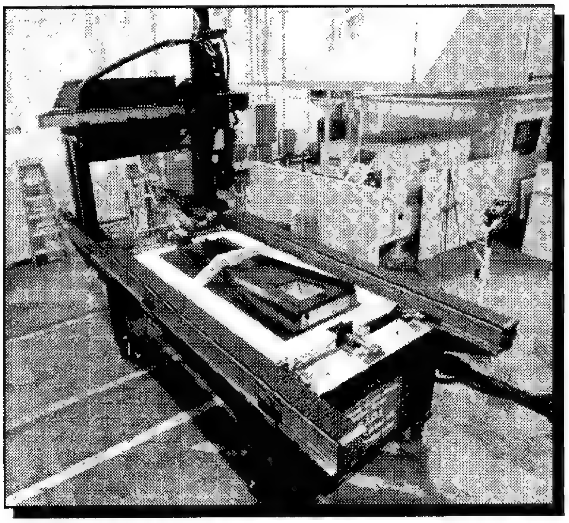


Figure 16 Reconfigurable Electronic Gantry Automated Drilling System (EGADS)

Our Electronic Gantry Applied Drilling System (EGADS) was assembled from commercial components in six months time at a cost of only $250,000. With motion capability of 10 feet linear travel, 5-axis and 360 degree rotation, driven by the 3D CAD model, the EGADS can find and orient itself to the part, eliminating the need for drill tools and master models. By simply changing the CAD model, the EGADS is insensitive to part configuration. The tool bed rotates to give back side access for drilling. Equipped with a vision system, the EGADS is capable of Statistical Process Control and Self Inspection of drilled holes. EGADS has been demonstrated on composite and aluminum parts and has achieved a $C_{pk} > 4.6$ with a $C_p > 2$-- measures of process repeatability within tolerance.

Once on the Shop Floor, we have implemented the Paperless Factory via our Integrated

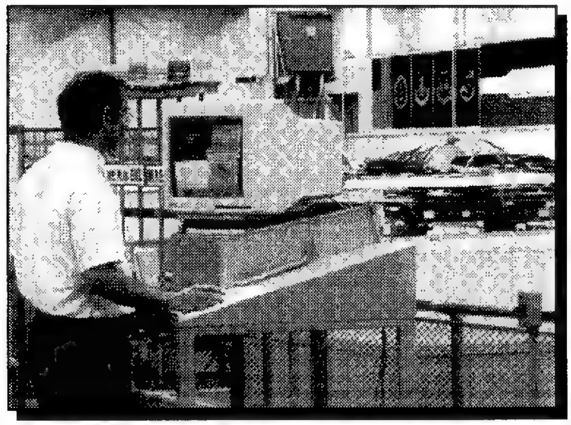


Figure 17 Integrated Management Planning and Control for Assembly System (IMPCA)

Management Planning and Control for Assembly (IMPCA) System. IMPCA is an on-line real time planning system which provides graphical work instructions with automated change control. It provides cost and schedule status, as well as on-line liaison and quality assurance buy-off and defect reporting. IMPCA serves as a total final assembly, factory floor control system.

We have shown how the common 3D electronic database can reduce design cycle time, ensure design for manufacturing, eliminate mock-ups, development fixtures and prototypes and optimize factory planning prior to commitment to design and hardware. The common database eliminates as many as seven layers of interpretation and potential for variability between the designer and final hardware product.

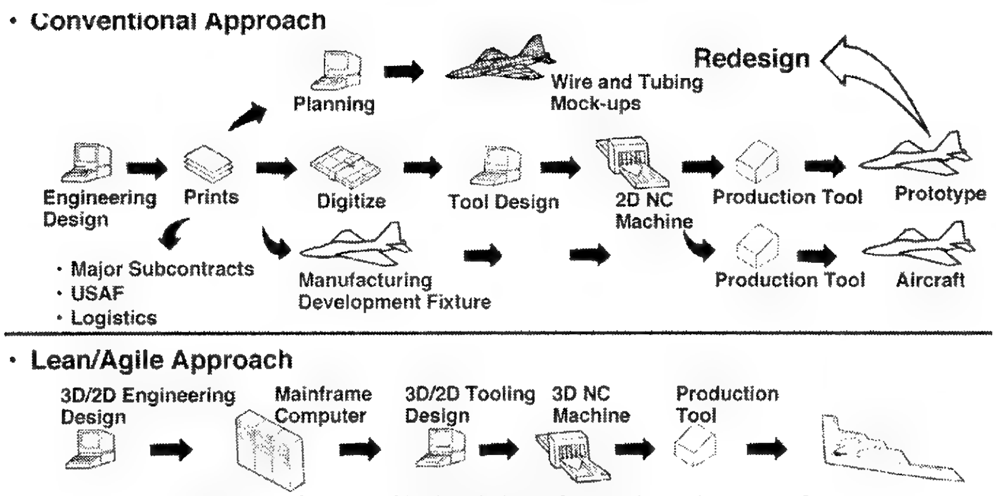


Figure 18 Lean/Agile Manufacturing Approach Eliminates Intermediate Process Steps.

Our Vision for the Future leverages continuing advances in

- Massively Parallel Processing
- High Speed Networking via the Information Superhighway
- Feature Based Modeling
- Increased Object Realism
- Advanced Visualizations

to achieve a Fully Integrated Virtual Production Environment.

Under this new paradigm, it will be possible to invoke a virtual "Art to Part" production methodology to evolve from wire frames to animated final assembly simulations and to validate proposed lean/agile production techniques before making production commitments.

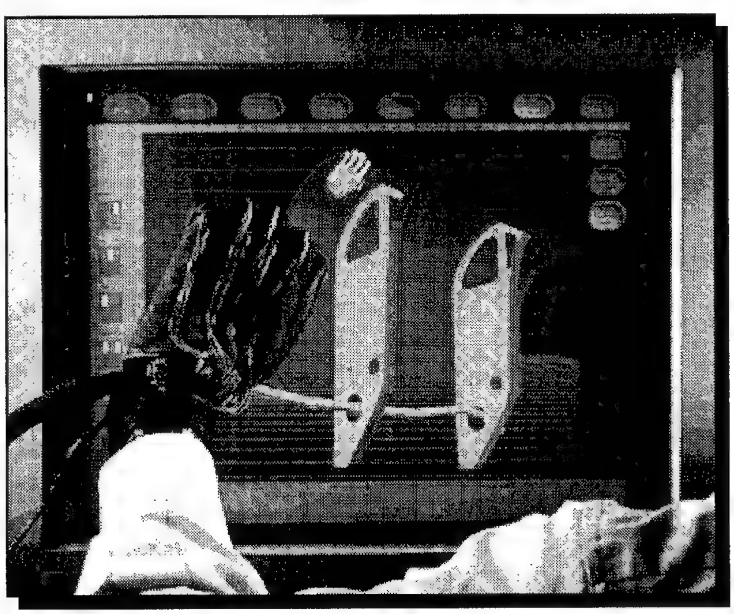


Figure 19 - Integrated Virtual Design Environment

[1]Integrated Airframe Design at Lockheed Martin Tactical Aircraft Systems

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Summary

Airframe product design integration is continuously evolving with the goal of facilitating the design team's mission; development of "build-to" datasets that provide the complete definition of hardware to be manufactured. This paper surveys design tools, practices, and strategies in Lockheed Martin Tactical Aircraft System's (LMTAS) integrated environment. Airframe design is a set of structured and chaotic processes coordinated to establish product function and fit, affordability, producability, and structural certification. Integration encompasses the data development, data transfer, and knowledge development necessary to create the product. Evolution of integrated design at LMTAS is resulting from influx of advanced technologies such as scientific visualization, multidisciplinary analysis and optimization, and data exchange standards. Illustrations of advanced technologies and their implementation at Lockheed Martin Tactical Aircraft Systems are provided in the context of conceptual design, preliminary design and detailed design.. New aircraft design programs offer opportunities to evolve integrated design.

Introduction

Airframe design at Lockheed Martin Tactical Aircraft Systems (LMTAS) is a coordinated set of processes integrated at the Design functional level. Integrated design refers to the design processes of data development, data transfer, and knowledge development. Data development and data translation enable design discipline integration. For instance, data exchange standards allow extraction of computer aided design data for construction of finite element models in third party software. Knowledge development strategies apply design disciplines in an integrated fashion. For instance, multidisciplinary analyses are used to evaluate a series of parametric variations of geometry for system level behavior.

Historically at LMTAS, the Design function has coordinated activity and integrated requirements in the areas of producability, affordability, fit and function, and structural certification (see Figure 1). Each area depends on Design for data origin at task initiation as well as inscription at task completion. Designers at LMTAS are trained in multidisciplinary skills, commanding general knowledge in each area, Historically, they have been responsible for function and fit of the design, as well as coordination and integration. Recently, LMTAS has placed emphasis on an integrated product team approach, where the coordinator is not necessarily from Design. The process, however, is still integrated in design to complete the "build-to" dataset.

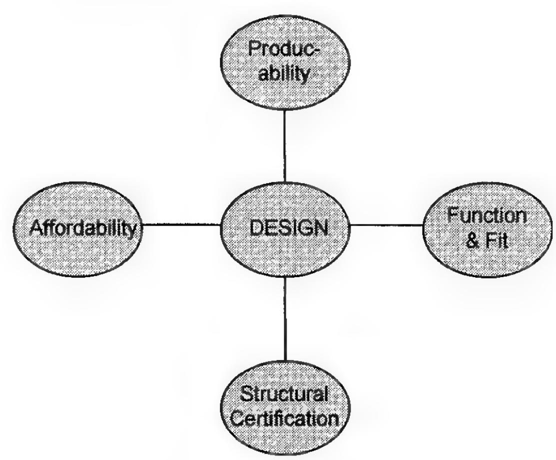

Figure 1 "Build-To" Data Is Integrated Through Design

The "build-to" datasets describe the hardware to be manufactured. They are typically derived from a computer aided design (CAD) package, and include geometry, materials, fabrication

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

processes, assembly instructions, and key analyses. Prior to product completion, the product definition is maintained in the CAD datasets and documented analyses.

Design integration requires data transfer capabilities between tools, including extraction from CAD packages as well as translation between analysis domains. An open framework of data storage is prefered to allow use of many in-house cultivated processes and tools.

Integrated design is a conscious effort of tasking processes to develop essential knowledge allowing strategic decisions that account for all design requirements. It is mission dependent. For instance, a design more prone to flutter requires more flutter analyses during the course of design. It relies on trade studies. The LMTAS integrated product team philosophy is to ensure that essential requirements are considered during the trade study process. The strength of LMTAS integration is derived historically from the coordination skills of our Design function.

Advances in design integration have resulted from use of maturing technologies such as multidisciplinary analysis and optimization, data exchange standards, and scientific visualization. These technologies allow more timely and extensive trade studies. They have provided shortened design cycles and greater consideration of detail within the design cycle.

Within academia and government laboratories, design is once again recognized as an engineering discipline requiring research and development. Besides the above mentioned technologies, emerging studies including quality function deployment (Ref 1) and design process decomposition (Ref 2,3,and 4) are showing promise. LMTAS is a culturally driven organization, and new processes in design are implemented in a building block fashion. Discussion of new technologies and their implementation is included in the following status of integrated design at LMTAS.

<u>Data Development and Data Transfer</u>
As illustrated for structural certification in Figure 2, varied processes in airframe design make up the total integration picture. At early stages of design, airframe properties are merely parametric. Once the vehicle design is stable, airframe issues can be analyzed and integrated.

Activity within configuration development includes vehicle sizing and performance verification. Wind tunnel tests are conducted

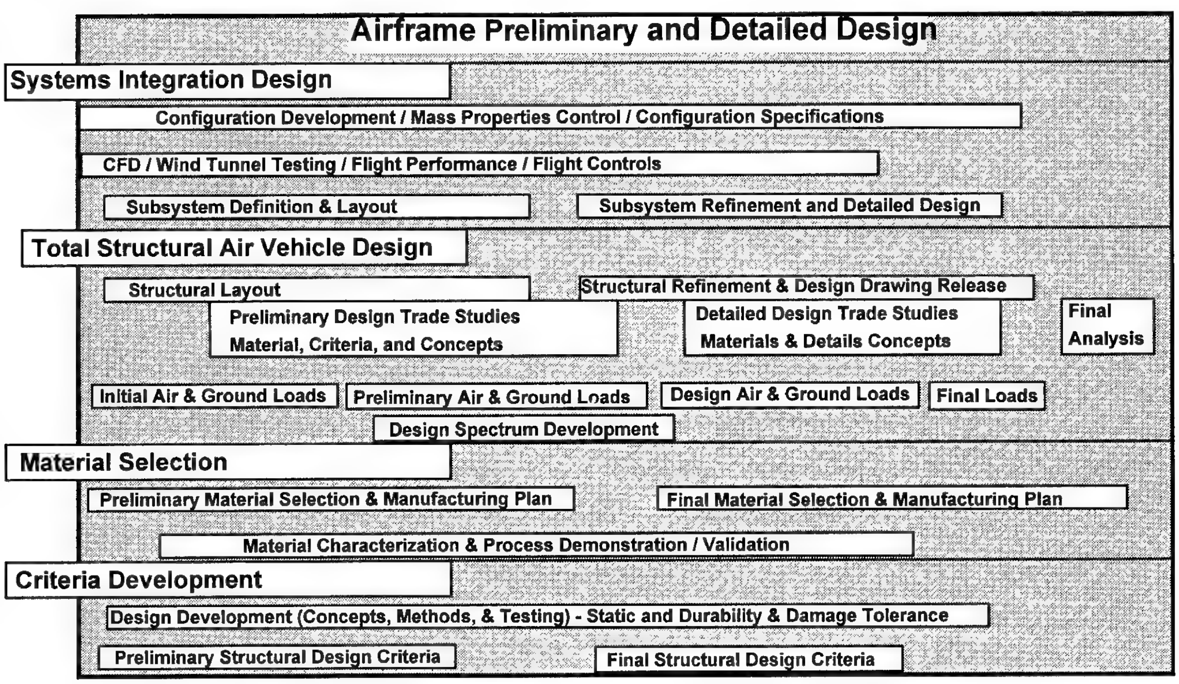

Figure 2 Many Processes Integrated Concurrently For Structural Certification

and subsystems locations are determined. Airframe structural layout studies are integrated through coordination and sharing of CAD system data. Studies include producability, costing, and functionality. Structural arrangements are analyzed as well with internal load models of the total air vehicle, and the process is iterated until the vehicle goals and requirements are met. During the course of the design, materials and structural concepts are selected. Initial input to the structural arrangements, loads models, and design criteria vary from established databases (mature concepts) to developing databases. Building block tests of structural concepts, design and analysis methods, and applied loads are matured and sequenced into the structural design iterations.

Configuration development relies on integrated layout of subsystems, flight controls and structural arrangement. For conceptual design, LMTAS has used an in-house package known as ACAD (Advanced Design Computer Aided Design - Ref 5) since the mid 1980's. ACAD was developed to respond to the dynamic needs of early design. Large mainframe programs were found to be limiting in response and user friendliness. In preliminary design, ACAD and CATIA (Ref 6) are used in complimentary fashion to provide timely transition from still ongoing conceptual studies and newly initiated detailed studies. ACAD does not have features fully developed for taking product data to hardware as CATIA does. Therefore, CATIA is used in detailed design almost exclusively.

The Initial Graphics Exchange Specification, IGES (Ref 7), has provided basic capabilities to allow this sharing between two CAD systems. While IGES has allowed satisfactory results, its performance has been data configuration dependent. The importance of data translation, however, is far greater than communication between our two CAD systems. LMTAS works with many vendors, and specification of design data as a deliverable in electronic format is reality. The design dataset paradigm is changing to a generalized dataset rather than a CATIA dataset or an ACAD dataset. Therefore the maturation of data exchange technology, specifically the Standard for Exchange of Product Model Data, STEP (Ref 8), should allow a seamless data environment. LMTAS has been actively involved in the development of STEP (Ref 9), and pursuing prototype applications.

A key element of integrated airframe design is the internal loads model. This model reflects status of design -cost, -manufacturing concepts, and -function/fit, and it provides for physics based analyses of the design's behavior. The loads model development process cycles continuously until the design is completed. The status of CAD systems and analysis modeling tools allow use of physics based simulations from the stable stages of conceptual design and is eliminating the distinct lines between the historical phases of conceptual, preliminary and detailed design.

The transfer of data in the internal loads model process as shown in Figure 3, includes the following:

1) CAD dataset to the finite element model mesh.
2) Finite element model geometry and stiffness to the applied loads model.
3) Applied loads to the finite element model.
4) Finite element internal loads to structural sizing tools.
5) Structural sizing requirements to finite element model and design dataset.
6) Mass properties to loads model.
7) Airframe flexibility effects to air vehicle system performance.

Finite element models are developed through the use of commercial tools as well as some in-house developed tools. Tools such as MacNeal Schwendler's P3/PATRAN (Ref 10) and Structural Dynamics Research Corporation's I-DEAS (Ref 11) provide evolving capability to interface with both CATIA and ACAD data. The ACAD program also has an embedded mesh capability and like CATIA, utilizes the design dataset directly. The ACAD mesh capability has been used in preliminary design while PATRAN and I-DEAS have been used in detailed design. Specialty modeling tools have been developed in-house to provide rapid modeling of lifting surfaces and thus, rapid assessment of aeroelastic effects on applied loads. None of the commercial tools have "ready made" templates for such rapid assessments.

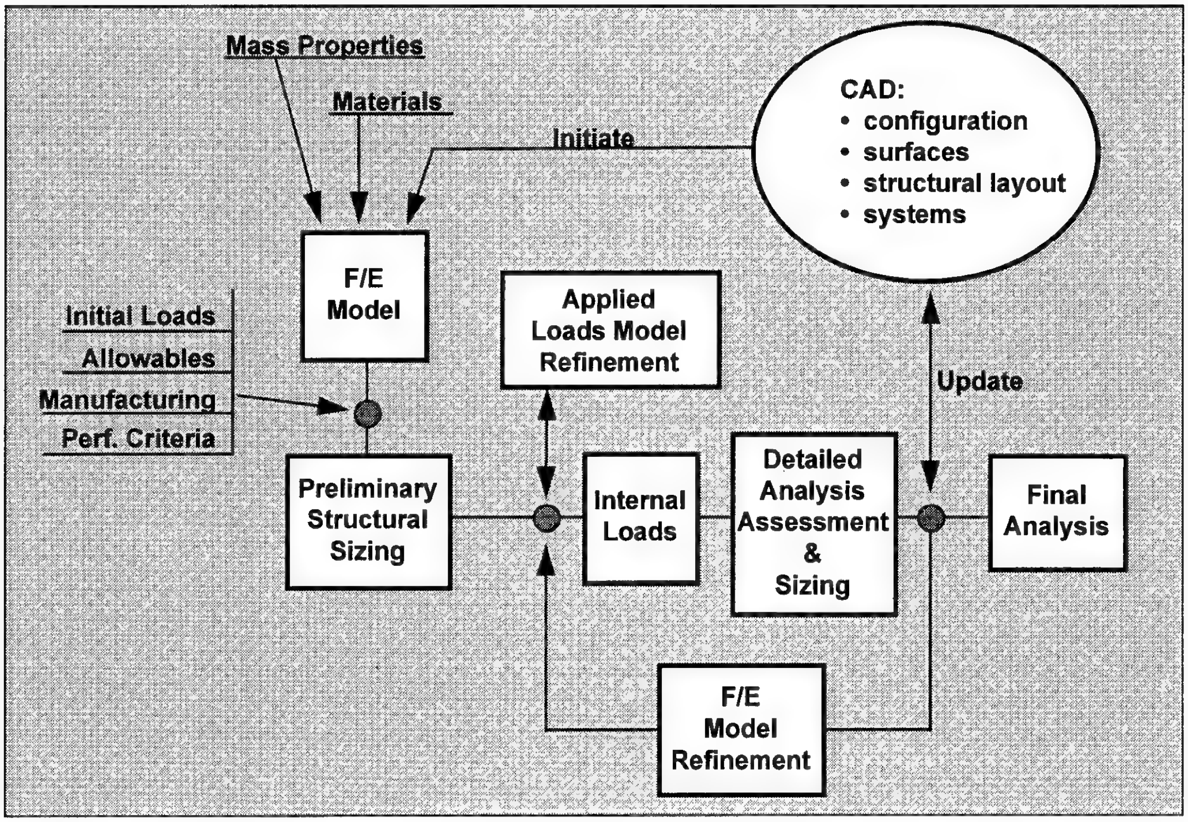

Figure 3 Internal Loads Development Process

The CATIA modeling tools' acceptance has been slowed by the lack of availabile versions for the high end engineering graphics workstations in lieu of mainframes. Competition within the commercial market will continue to drive tool development, and LMTAS is continuously evaluating tools for process improvement.

Construction of the finite element model translates the design into the finite element domain. Modeling includes capture of key manufacturing assembly features (fittings), structural arrangement (bulkheads, frames, longerons, spars, and ribs), manufacturing concepts (material properties), and subsystems (actuators). Consequently, finite element modeling at LMTAS is a process that requires communication with Design to understand and translate the above mentioned features.

Once the design is captured, it takes on a life of its own until the configuration is no longer valid or the design has matured to a point of the "build-to" dataset release. Integration (in a data sense) becomes a task of streamlining the transfer of data as described above in items 2) through 7).

The first task after the finite element model is complete is that of preliminary sizing. Historically the aircraft industry has used rigid loads for initial sizing. In follow-up tasks, stiffness matrices are acquired for the computation of aeroelastic corrections to the loads, and the model is sized in greater detail.

Typically NASTRAN[2] is used for finite element modeling of internal loads. The NASTRAN "bulk data" becomes the database of the design as it exists in the analysis world. None of the commercial modeling products have enough consistency in data storage and retrieval for maintenance of all the properties of the loads model. The STEP technology (Ref 9) being developed should remedy shortcomings in commercial tools that preclude data consistency, and commercial modeling companies are involved. Also, NASTRAN is used in airframe design due to the familiarity our customer has with the product.

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[2] NASTRAN is a trademark name for the structural finite element analysis program developed by NASA in the 1960s.

Linear panel aerodynamic methods are used for the applied maneuver loads in preliminary design. As the design progresses, a semi-empirical database is constructed from the knowledge gained in force model testing. And most recently computational fluid dynamics (CFD) data is used in lieu of yet acquired wind tunnel pressure data. CFD, like any analytical methods, requires test-to-theory correlation, and complete replacement of wind-tunnel testing with CFD is not anticipated by this author.

Recent configuration studies at LMTAS have used Euler and Navier-Stokes CFD results coupled with available wind tunnel pressure data for similar vehicle components. The CFD predictions for the test configurations and the new vehicle design were used to bridge the configuration differences, and the test data provided 'anchor points' or verification of pressure levels. A large matrix of loads data can be generated by creating mathematical blending through linking of CFD, test data and geometric data. It has been found that the use of Navier-Stokes solutions is becoming more necessary in cases in which flow separation or shock-boundary layer interaction is significant. Fighter-type vehicles have a wide performance and loads envelope, so that these Navier-Stokes cases are a significant percentage of the CFD run matrix. Also, for slender vehicles, the Navier-Stokes predictions create more-accurate representation of lee-side pressure distributions from vortical structures. Use of purely Euler or full-potential solutions for loads development may not provide the resolution required for detailed structural sizing or hinge moment determination.

Final loads are determined with the aid of wind tunnel pressure data. The loads data is fit to the finite element model for aeroelastic corrections using such techniques as the infinite plate surface spline of Desmaris-Harder (Ref 12). The FLEXLODS (Ref 13) program provides the basic static aeroelastic analyses. In-house maneuver load simulation procedures assemble mass properties, aerodynamic pressures and aeroelastic corrections for load surveys and selected applied-load compilations.

Data translation from the finite element model to the loads model and back is currently provided through LMTAS customized software. A library of routines is maintained that provides for use of databases to fit trimmed maneuver loads data to the finite element model. The maneuver loads model is correlated with the flight controls maneuver simulation procedures to ensure accuracy in the loads. The process is cultural with respect to the expertise and familiarity of the individuals performing the discipline.

For the last twenty years multidisciplinary design methods have provided for integration of aeroelastic requirements (i.e. aeroelastic loads, controls, aerodynamic performance, and flutter) in the initial sequence of sizing; thus eliminating the rigid loads cycle for the most part (Ref 14). In this practice, studies have been conducted with the Wing Aeroelastic Synthesis Procedure (known as TSO) to determine initial structural gages for aeroelastic surfaces such as wings and tails. TSO is a Rayleigh-Ritz based tool that includes linear steady and unsteady aerodynamic panel methods as well as nonlinear optimization in an aeroelastic modeling capacity for the design of lifting surface structures.

Most recently, the ASTROS program (Ref 15) has been incorporated to provide greater flexibility and detail in the initial sizing phase. ASTROS is a finite element based system (see Figure 4) developed around a multi-schematic database and architecture. It includes linear steady and unsteady aerodynamic methods that can be coupled with the structural finite elements for aeroelastic solutions. It also includes optimization techniques to allow the simultaneous sizing of structure to strength and aeroelastic requirements. ASTROS has been under development through U.S. Air Force sponsorship since 1983, and it is available commercially today.

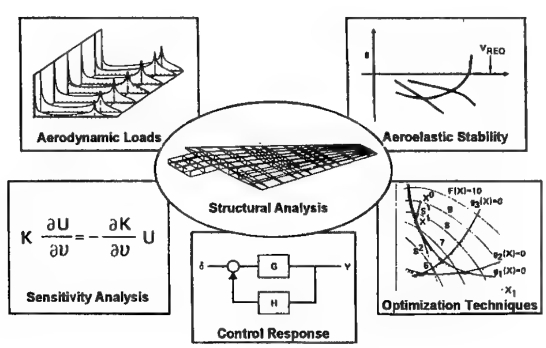

Figure 4 ASTROS Is A Multidisciplinary Design Tool

Figure 5 illustrates a philosophy of ASTROS usage in the internal loads process. In the course of developing initial structural gages for the internal loads model, ASTROS studies provide feedback to configuration development in the form of structural weight, control requirements, and aeroelastic effects on drag. Improvements over the previously used tool, TSO, include accounting for structural arrangement, manufacturing and material concepts, and other configuration integration features such as wing aspect ratio and fuselage fineness ratio. ASTROS also provides feedback to the internal loads model that is dependent on material selection, manufacturing processes, and design criteria. Within ASTROS, maneuvers, aeroelastic criteria, and strength criteria are defined, and the structure is sized.

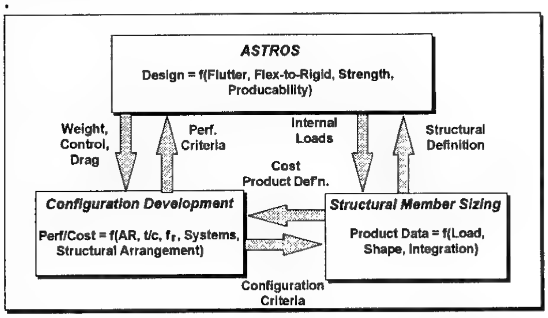

Figure 5 ASTROS In The Internal Loads Process

In using ASTROS the number of resize cycles necessary to arrive at a converged internal loads model is reduced. The next task within the sequence displayed in Figure 3 is a detailed sizing of the structural model. At this point, an expanded set of aeroelastic loads are developed that are reflective of the structural stiffness of the initial sizing. In comparison, an ASTROS optimization model might include four static aeroelastic cases and four static cases, and the detailed model sizing task might include approximately twenty load cases.

With the new internal loads, actual airframe parts (e.g., bulkheads, spars, control surface core) are analyzed with a combination of "hand crank" methods and specialty programs (e.g. a program for composite bolted joints). The internal loads are saved in databases constructed from in-house methods that facilitate min/max load surveys on element-by-element basis. Detailed parts are defined as a collection of elements. Hand crank and specialty strength analysis programs have been compiled into menu driven scripts that provide user friendly and timely analyses.

At this point of the internal loads cycle, the structural model is updated with changes in the configuration structural arrangement as well as the required structural gages. Data is also passed to the structural arrangement with regard to feasibility and integrity requirements. The cycle is then repeated unless the design is considered to be complete or the configuration is no longer valid.

Another advanced technology enhancing the design process is scientific visualization. Tools utilizing this technology allows designers and analysts to rapidly attain visual account of the behavior of a design. In the internal loads process, structural deflections, stresses, mode shapes, and aerodynamic pressures are typical data reviewed. Methods for visualization range from in-house generic polygonal-display software to commercial packages such as I-DEAS and P3/PATRAN. Figure 6 displays pressures from a computational fluid dynamics solution with a store drop.

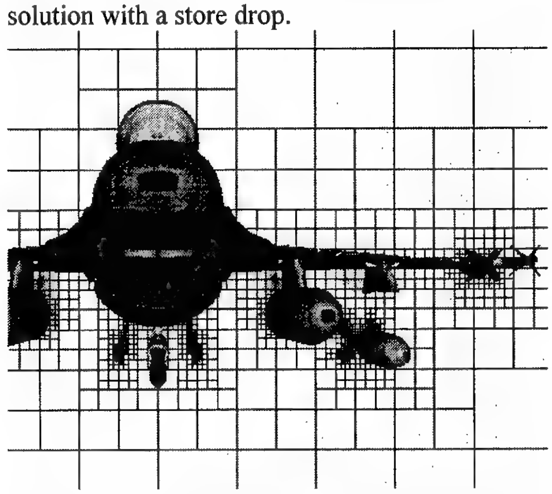

Figure 6 Visualization of Pressure Data To Support Aircraft Loads Development

Scientific visualization has enabled LMTAS to use computer mockups in lieu of hardware mockups. In the structural layout phase, assembly mockups are constructed in the virtual sense. Display capabilities of ACAD, CATIA, as well as in-house software are utilized. Figure 7 displays a typical aft fuselage section. Systems integrated with the airframe are inspected for interference and other assembly problems. In. the integrated product team approach to design, portions of the airframe are organized into zones, and the design of each zone is integrated through

the product team analysts, airframe and subsystem designers, manufacturing and tooling designers, and reliability/maintainability engineers. The computer mockup provides integrated datasets of the design. Interference and tolerance analysis tools are coupled with the mockup datasets to assure assembly integrity.

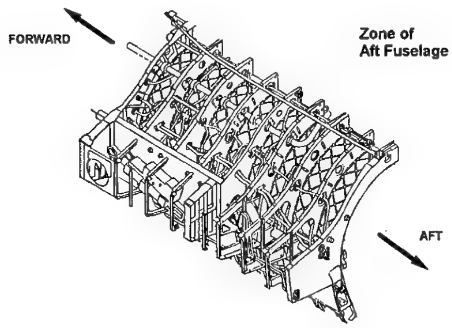

Figure 7 Visualization Is Enabling Virtual Design Environment

Knowledge Development

As previously described, design is a coordination of existing processes to evaluate candidate concepts. At LMTAS, concept evaluations usually take the form of trade studies. Key parameters are recognized and evaluated in an effort to determine the best design candidate. Trade studies usually involve a combination of quantitative and qualitative criteria, and each of the concepts are scored. Figure 8 illustrates the structure of a trade study.

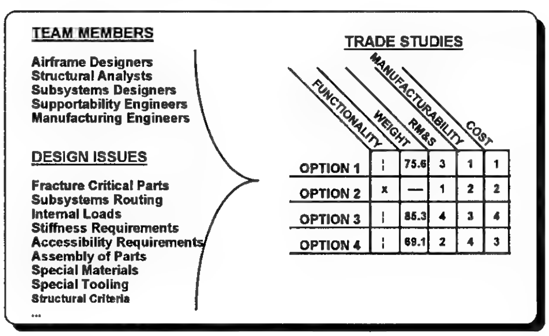

Figure 8 Trade Studies Are The Backbone To Design Decisions

The LMTAS design development process is both structured and chaotic. It includes the use of very structured processes to allow such aspects as multidisciplinary analyses. However, many of the processes are independent; thus creating challenges for coordination (e.g. structural certification of new design concepts with production process development of design concepts). An ideal integrated environment would allow concurrent communication of all essential requirements to the disciplines that need them and also simultaneously allow each discipline process to be uncoupled from any iterative sequential path; thus providing a concurrent integrated design. In practice, increasing levels of integration occur with each design cycle; past design experience provides for many design decisions; some decisions are made arbitrarily due to lack of resources (e.g. money, schedule, capability); finally, a number of design decisions are selected for study. The studies engage processes such as internal loads development, detailed part design with parametric extrapolation, producability and cost projection, and detailed structural layouts and sizing.

As mentioned in the introduction, design methodology is an active topic of research in the world today. Techniques such as Quality Function Deployment (QFD) are being examined and occasionally used. In QFD, the designers develop lists of requirements and desired design features. These two lists are analyzed in matrix format to assure that the design features cover the requirements. Goals are established for the design features. This technique has never been instituted as a formal process, yet it is used in good design practice informally through understanding and satisfying requirements.

In a recent conceptual design study, global sensitivity equations, GSE (Ref 3), were developed for the complete configuration and used to modify an existing concept. Airframe parameters considered included weight sensitivities with respect to aircraft service usage and aircraft flight envelope. These sensitivities were derived and calibrated from an existing design. Detailed sizing techniques were used to extend the baseline design and preserve accuracy in the sensitivities. To be used more fully in airframe design, this technique requires the ability to cast the design into a continuum. Many of airframe design measures are functions of discrete parameters and have merits that are qualitative rather than quantitative. This author believes that GSE methods will gain increasing acceptance in areas of quantitative evaluations.

Improvements in data exchange processes and CAD (computerized mock-up and scientific visualization) are providing the capability to examine more discrete design choices. These choices as mentioned are often measured on some merit of "goodness" and therefore scored - A,B,C or 1,2,3. However, increasing use of structural optimization is also providing a quantitative measure of goodness. It seems that this capability to measure the design leads to examination of more "what if" trade studies in the length of time allotted for design.

Process decomposition (Ref 2,4), like QFD, is a design tool that is used at LMTAS without formal implementation. An example of such is in the design for controlling the aircraft. While the control law group assumes certain flexibility effectiveness values for the structure, the structural designers strive for those effectiveness values through multidisciplinary design methods. Airframe design is utilizing this technique increasingly because of the ability to produce and quantify concepts in rapid fashion. Each discipline performs parametric analyses and then meets to determine where the optimal compromises are.

Structural optimization trade studies include independent variations on discrete structural arrangements, design criteria, materials and manufacturing concepts, and system level performance parameters such as control effectiveness. One study of structural arrangement in a concept design phase examined a mid-fuselage wing interface versus a continuous wing over the fuselage interface. In a current case, discrete whole vehicle concepts are being sized and evaluated. Design criteria studies have included variation of material allowables derived from severity of service life usage.

Examples

Provided in the concluding pages of this paper are two examples in which multidisciplinary design techniques are impacting system level design decisions. The first study involves the conceptual design level, while the second study is an example of the preliminary design level.

The Wing Aeroelastic Wing Procedure, TSO, was used in the 1980's to provide data for the selection of the wing planform (Ref 16) in a conceptual study. Candidate configurations are shown in Table 1 and Figure 9.

Table 1 - Candidate Wing Configurations

Config.	Span (ft)	Area (sq ft)	Sweep
# 1	37.50	375	40.0°
# 2	35.07	375	37.5°
# 3	35.07	410	37.5°
# 4	35.07	328	37.5°
# 5	33.54	375	37.5°
# 6	37.50	375	37.5°
Baseline	37.50	375	34.3°

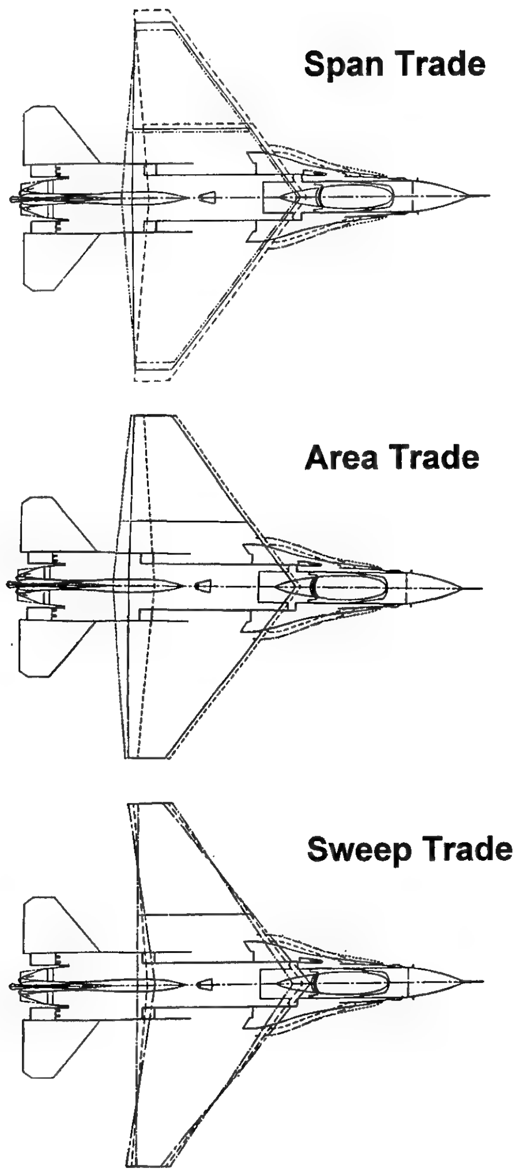

Figure 9 Three Planform Trades

Parametric variations in wing span, wing area. and wing sweep were examined. While structural optimization studies were being performed, wind tunnel testing and aerodynamic analyses were conducted.

Typical optimization results utilizing varying levels of aeroelastic tailoring were derived and are shown in Figure 10. The wing box skins were designed in each configuration for three different design goals/concepts. A minimum weight "Strength Sized" design was achieved with three aeroelastic load cases (two symmetrical pull-ups and one asymmetric rolling pullout). In the second concept, a flutter requirement and an aileron roll effectiveness requirement was added to the strength requirements ("Aeroelastic Sized"). The third concept added an aeroelastic twist requirement to the strength and aeroelastic requirements. The aeroelastic twist provides Lift-to-Drag efficiency at the simulated turn maneuver point.

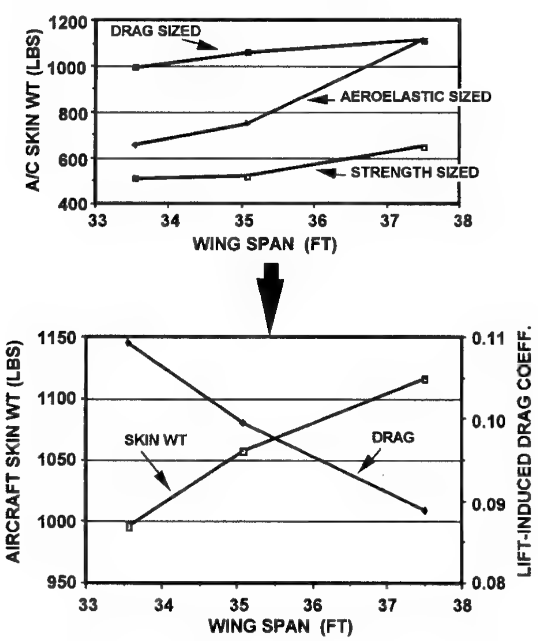

Figure 10 Optimization Study Examined Weight, Design Concepts, and Performance

The top part of Figure 10 displays the sensitivity of the wing box skin weight with respect to the concepts and span. The span study (shown above) provided the greatest sensitivity while the sweep (not shown) provided the least. The bottom part of Figure 10 provides the sensitivity of the aeroelastic drag to the wing skin weight for the "Drag Sized" concept.

This study provides valuable data to be used in conjunction with the stability and control and the aerodynamic performance results. While this study was performed in the Wing Aeroelastic Synthesis Procedure (TSO) in the 1980's, the same study might be performed in ASTROS today.

The second example provides indications of ASTROS capabilities in a look at structural weight to roll rate. Other studies performed with ASTROS at LMTAS have included variations of material selection, material allowables, structural geometry, and design criteria. This study exemplifies ASTROS' use in the process of developing knowledge to "what if" questions commonly asked in design and demonstrates the learning resource optimization methods provide to design.

In the TSO study described above, the structural model is a Rayleigh Ritz representation of the wing-only. While a similar air vehicle is subject in the this study, the structural model includes a beam fuselage with a built-up wing and tail finite element representation.

Contrasting TSO with ASTROS, the TSO model allows only the wing to be a flexible aeroelastic surface. The ASTROS models can be completely linked aeroelastically through the infinite plate surface spline imbedded in ASTROS. For this study, two symmetric cases are included for strength (+9g pull-up and -3g push-over). Two antisymmetric conditions are included for the roll effectiveness condition (subsonic flaperon only case and supersonic flaperon/horizontal tail blend). Figure 11 shows the structural finite element model and the linear panel aerodynamic model.

The objective of the study is to identify a threshold level of roll effectiveness at which the design of the structural wing box skins imposes rapid increases of weight. This issue has historically required coordination of structural design and flight controls design. Aeroelastic tailoring practices allow trades of weight to aeroelastic performance and can delay the onset of weight increase. Thus the study requires a series of optimization results with a parametric variation in roll effectiveness.

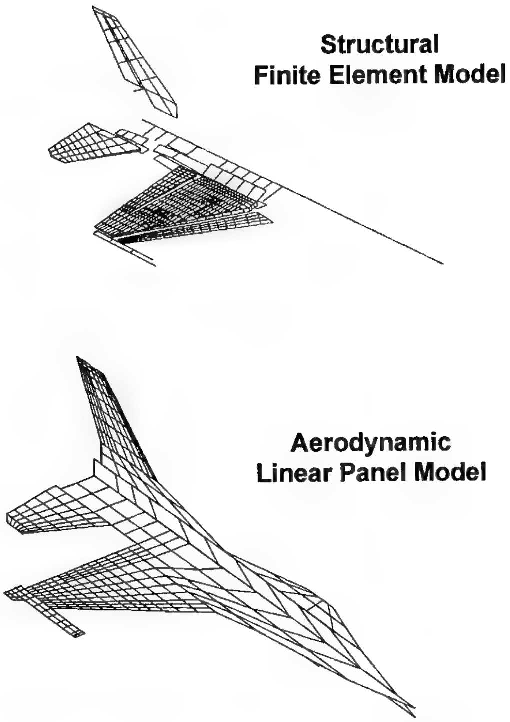

Figure 11 Analysis Models for ASTROS

To begin the study, a baseline aluminum skin design is acquired. Ensuing designs with ASTROS consist of aeroelastic tailoring with composite wing box skin material. Each design represents a correlation to the baseline aluminum design with incremental improvements to roll rate performance. Figure 12 displays results at roll rate values increasing to 45% improvement.

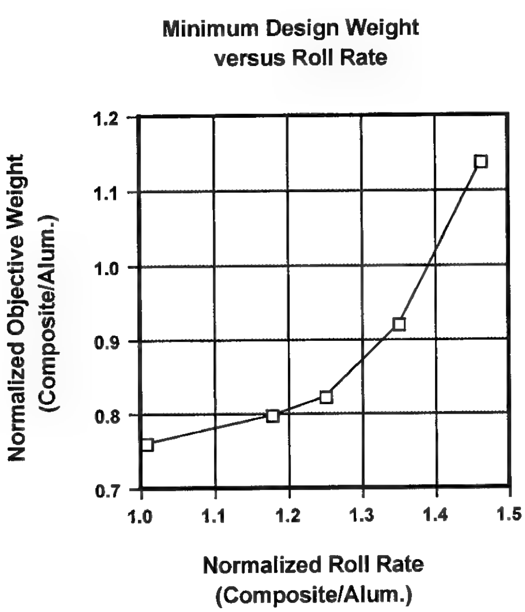

Figure 12 Vehicle System Sensitivity

A threshold level for weight increase to roll rate increase appears at approximately 25% improvement over the aluminum baseline. This design would provide the initial sizing for the applied loads, internal loads development for the entire vehicle, and detailed design assessments once a built-up fuselage finite element model is constructed.

While the above results may seem ordinary, the mechanics of the results are not. The optimization model and algorithm drives the aeroelastic tailoring concepts to minimize structural weight. Since this vehicle has only an inboard control surface involved in the roll effectiveness parameter, the algorithm and models exploit the outboard portion of the structural box. The design produces washout aeroelastic behavior under load (twist in such a way to relieve load). Figure 13 shows the trend of aeroelastic twist and roll rate.

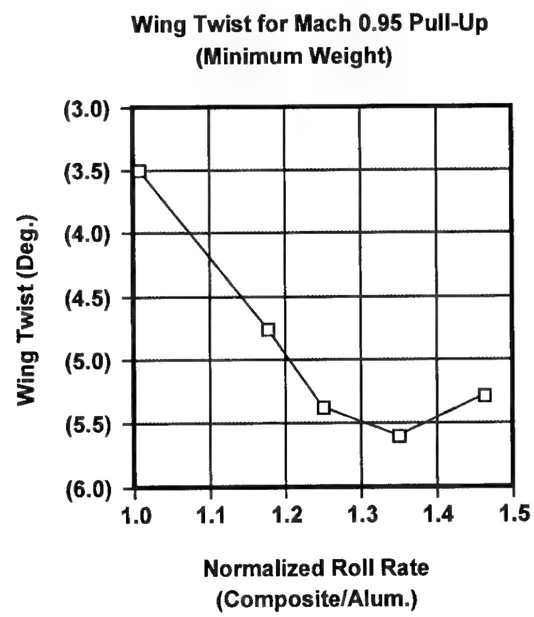

Figure 13 Aeroelastic Twist Relieves Loads In Symmetric And Antisymmetric Conditions

As the roll rate requirement is incremented, the design space allocates enough room to add composite material promoting bend-twist couple. This couple not only relieves load under the strength critical symmetric load conditions but also relieves damping load under the antisymmetric roll conditions. The bend-twist couple designed into the outboard wing panel

increases weight, but its load relieving action allows the inboard wing box to be slightly lighter. The curve in Figure 13 bottoms out between the 25% and 45% improvement levels in roll rate. Recall that the threshold level of weight increase was also at the 25% roll rate improvement.

Conclusions

Integrated airframe design at Lockheed Martin Tactical Aircraft has been examined. Design involves a coordination of structured and chaotic processes (probably common with other aircraft companies). It is integrated through activities that communicate and develop data for manufacturing, structural certification, costing, and fit/function. Integration results from cultural use of computational models, CAD, and trade study processes.

Advances in integrated design at LMTAS has arrived through influx of advanced technologies such as scientific visualization, multidisciplinary analysis and design, and data exchange standards. Commercial products such as CATIA, NASTRAN, I-DEAS, and PATRAN are intrinsic cornerstones to the integrated design process. These products are acquiring such technologies in order to remain competitive. These technologies have and are providing for an oncoming virtual design environment. Scientific visualization is allowing examination of virtual product mockups. Multidisciplinary design methods are providing for increasingly comprehensive trade studies. These tools need testing, and the design community needs to learn how to use them. Finally, data exchange methods are essential. Electronic data delivery is becoming standard practice, and design datasets are becoming more expansive than CAD.

Integrated design has been the culture and practice at LMTAS for many years. Older tools such as TSO were developed to expedite the integration, and newer tools such as ASTROS are used with CATIA and ACAD data systems in our current design practices. The greatest advances in integrated design have been made possible by tools that allow rapid physics based modeling of the design and its sensitivities. Consideration of flexibility and structural dynamics effects in design has been major benefactors of technology development. Modeling of manufacturing processes, design costs, and aircraft maintenance provide additional areas for technology growth.

Aircraft companies look to implement new tools in the design process at program starts. Integrated airframe design will continue to evolve with aircraft product development.

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A Common Framework Architecture for an Integrated Aircraft Design

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Summary

The paper first describes the architecture of the framework and the processes which are implemented. After that the concept of a common optimisation model formulation based on the design element method and its integration in the overall process is explained. As an example for the so-called "constructive design model" the optimal layout of a stiffened panel under buckling loads is considered.

1. Introduction

The simultaneous consideration of various design requirements already in the preliminary design phases has been recognized as a necessary step towards a virtual realisation of an aircraft. But in spite of the theoretical, computational and methodological progress that has been made in the last years in engineering design disciplines, their interdisciplinary interaction is not yet accounted for. This situation can be partly attributed to the fact, that communication between engineers and computer aided methods e.g. numerical aerodynamic codes or finite element codes requires handling of large volume of information which prevents innovative and creative decision making during the design process but forces the design engineers spending 50% to 80% of their time organising data and moving it between applications.

SiFrame[(R)] is a registered trademark of SIFRAME Software Technology GmbH

To overcome these difficulties a commercial available integration platform can be used which controls the execution of activities and stores all informations produced during the design process in a database.
Starting with a CAD reference model - stored in a common geometric database - as the basic description of the geometrical modeling of the constuctive layout, each engineering discipline in the design process can derive its own analysis variables, which are assigned to the geometrical parameters. For multidisciplinary design optimisation (MDO) tasks, parameters of the design elements (e.g. points, lines, curves, surfaces) can be additionally defined as design variables instead of the analysis variables of an analysis model.

2. The engineering framework SiFrame [(R)]

2.1 Process analysis

During the last years, detailed investigation of the as-is situation processes was performed at Dasa Military Aircraft /KRA93/VIL95/. Much attention was given to the relationship between internal client and service provider. The next step was to evaluate the identified weak points using the portfolio approach. The should-be concept is developed now based on the analysis performed.

With respect to process improvement the following focal points have been identified. The requirements with respect to the functionality of an engineering framework derived from these findings are given in Italics:

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

- Improvement of the processes by minimising and optimising the interfaces and avoiding incompatibilities in data exchange between tools (= > *process and data management).*
- Development of a systematic approach for defined release of preliminary information, because some processes may last a year or longer and a lack of information was visible for the follow-on process (= > *team work, communication).*
- Development of a product data model (STEP) to introduce a data management independent from the used IT-tools (= > *data management, data integration).*
- Introduction and integration of (new) tools, which will radically change and simplify existing process chains. There is much potential as well in local activities (improvement of the process chain within one function) as also in global, that means cross functional improvements (= > *tool integration, process integration).*

2.2 Framework architecture

One of the main problems which have to be solved in complex design tasks is the simultaneous and concurrent handling of two types of information:

- Engineering Data and
- Management Information

In typical complex projects a number of teams work in parallel on highly interrelated tasks. The framework supports the exchange of engineering data and information for team coordination. It ensures the controlled distribution, access and consistency of data. The framework architecture is used to coordinate tools and services specific to single design or engineering tasks. Management information which forms the basis for decisions, consist of official documents and contain all information necessary to document the product, depending on the rules valid in each company. The documents are made available in a controlled way to all participants of the product development and manufacturing process, management, customers and suppliers.

The framework controls the execution of activities for defined phases of the product design process. It serves as a common environment for teams of designers to perform parallel execution of their activities. The information related to the project generally consists of: teams, the process flows of the project and the tools used to perform the activities. SiFrame(R) manages the relevant files processed by designers and keeps track of the versions of those files. All information produced during the development process is stored in a database. The framework architecture is shown in Fig. 1.

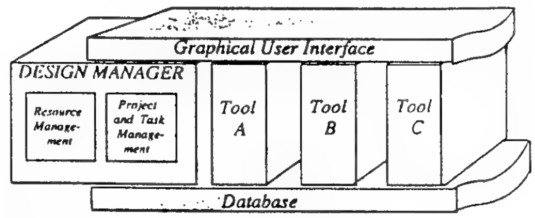

Fig. 1: SiFrame (R) Architecture

The main components are:

- **Graphical User Interface (SiFrame Desktop).**
  It visualizes all process relevant data using graphical objects. It uses either X-Window or OSF/Motiv on UNIX-Hardware and Microsoft-Windows on PC.
- **Design Management**
  It supports the definition, the administration and execution of projects (Project/Task Management). It further controls the application tools and the input and output data of these tools.
- **Inter-Tool-Communication-System (ITCS)**
  It supports the data communication between the integrated application tools using standardized interfaces.
- **Database Management System**
  It stores the process and project data and the process connections. Some of the objects which are used in SiFrame(R) and which have to be configured and defined before starting a project are shortly explained in the following (Fig. 2).

  Project
  A complex project is separated in tasks which can be managed by a single person or a team.

  Task
  A set of activities, executed in sequence or in parallel, as described by a process flow.

  Activities
  Activities define one single step in the process flow, using a specific tool or a subfunction of a tool.

  Viewtype
  Viewtypes are the input and output data of activities (Fig. 3).

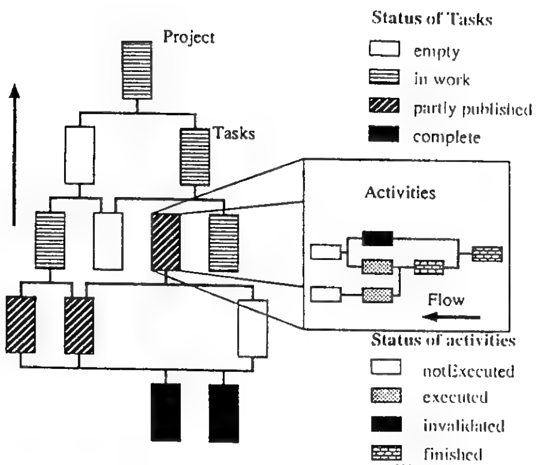

Fig. 2: Objects used in SiFrame(R)

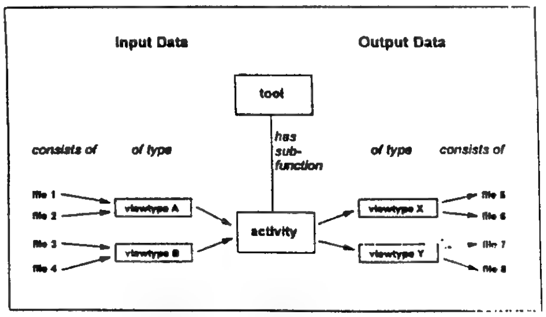

Fig. 3: Relations between Tools, Activity, Viewtype

2.3 Implementation of a simplified development process in SiFrame(R)

In a pilot study the simplified development process of a wing box segment (Fig. 4) was modelled and implemented in the framework.

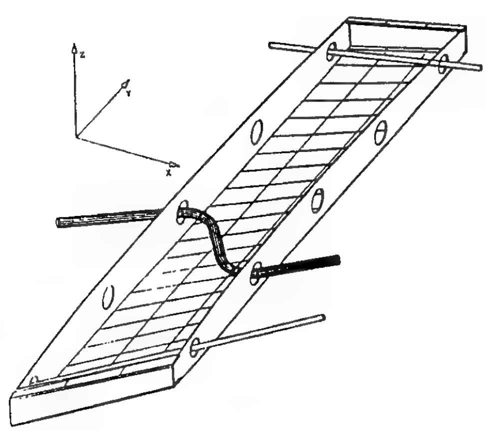

Fig. 4: Simplified wing box segment

Fig. 5 shows the four tasks which have been defined for the preliminary design stage. The result of this project is a released preliminary design.

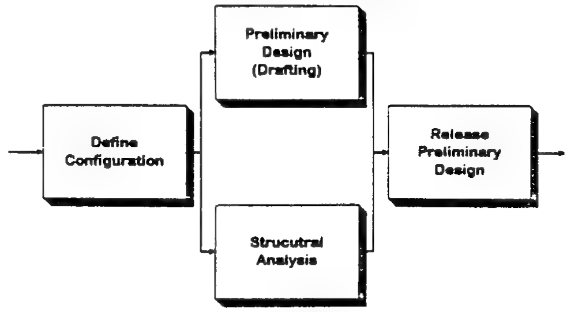

Fig. 5: Task structure of preliminary design

Inside of these four tasks process flows are defined, which can be seen in fig. 6 to 8 and are described as follows:

1. **Define Configuration**
   - Define external configuration: The CAD system CATIA is used for defining the wing shape.
   - Define internal configuration: The definition of the so-called system lines provides a first representation of the arrangement of the internal structure consisting of ribs and spars.

The following steps are carried out concurrent in two tasks:

2. **Preliminary Design**
   - A first draft of the structure is made.
   - The hydraulic system and drive units for the leading and trailing edges are designed in parallel using CATIA.
   - Finally, three models developed in the preceding activities are harmonised to avoid geometric collisions.

3. **Structural Analysis**
   - The task structural analysis is showing already a much more complicated flow, which is not explained in detail. The tool LAGRANGE and NASTRAN are used to optimize and analyze the structure and for creating the structural model and for visualizing the results (I-DEAS).
   (It can be seen easily, that this task was simplified by defining the structural loads by a simple editor instead of the relevant tools.)

4. **Release of preliminary design**
   - All information, which is available for the definition of the geometry of the proceeding activities are checked once again for consistence and an already well defined geometrical description of the wing box is released for the detailed design.

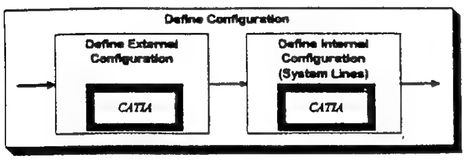

Fig. 6: Task "Define Configuration"

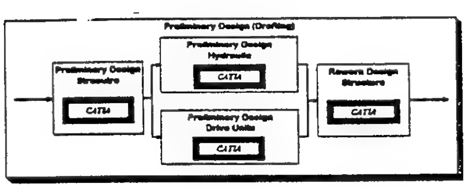

Fig. 7: Task "Preliminary Design (Drafting)"

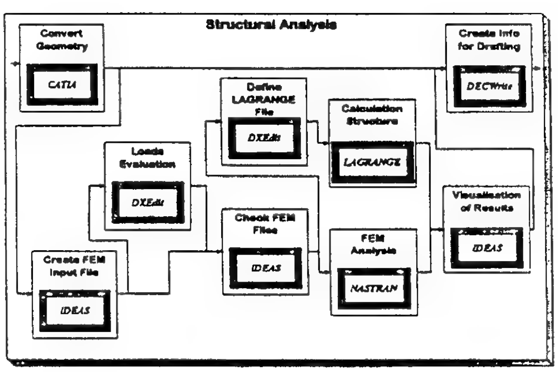

Fig. 8: Task "Structural Analysis"

The implementation was made in a Local Area Network (LAN) Environment, where the different tools are running on several UNIX-Hardware platforms (e.g. IBM RS6000, DECstation 5000) using a client server architecture.
In the context of the just started BRITE/EURAM Project "Multidisciplinary Design and Optimization of Aircraft" the usage of SiFrame(R) as a Framework which controls and coordinates the different contributing analysis (CA) is discussed. The lack of a direct iteration or "conditional jump" process control option in the process flow can possibly be solved by applying the state control of activities and tasks provided by the framework (Fig. 9).

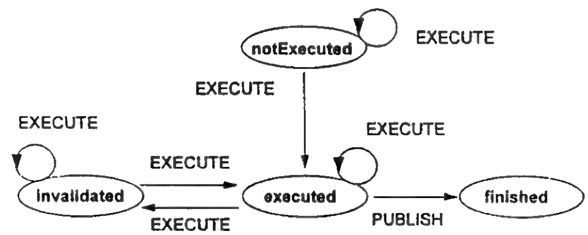

Fig. 9: Conditions of activities

3. Constructive design models for multidisciplinary design optimization

In the task "Define Internal Configuration" of the simplified wing box design process (Fig. 6), the arrangement of the internal structure is done manually by using the CAD-tool CATIA, based on the experience of the engineer without performing any structural analysis or optimization.
In the following a method is described which uses the CAD representation of the wing shape (the result of the task "Define External Configuration"), as the bases for an optimal layout of the internal structure.
As an example a plane or shallow curved fiber composite plate which consists of a so-called base panel with fixed stiffness according to Fig. 10 will be considered (/ESC95a, ESC95b/). This panel is assumed to be subjected to shear and compression loads. Plate and stiffness can be made of either isotropic or CFRP-material (Fig. 10b). Plane structures of the above-described type are generally endangered by buckling, the buckling value can be

maximized by choosing certain design influence parameters like the thickness distribution, the stacking sequence, the ply angles and ply thicknesses of the base panel, or the arrangement, shape or number of stiffeners.

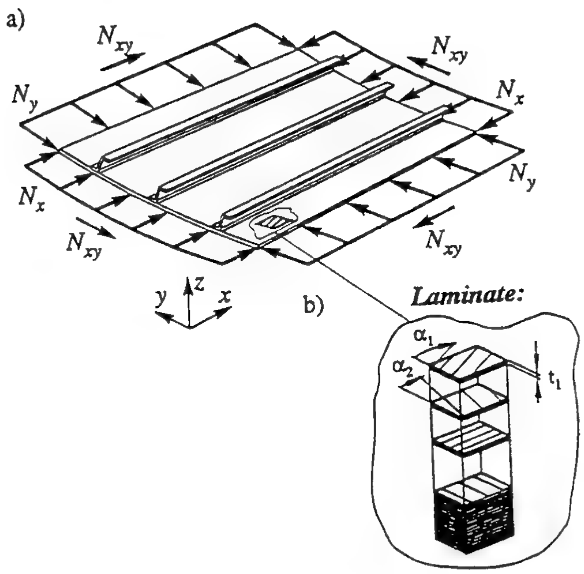

Fig. 10: Stiffened composite panel

Thus, the optimal layout of such a panel shall be determined, where imperfections and the postbuckling behaviour shall not be considered in the layout.

3.1 Problem

Definition
The given optimization problem can be formulated in the following way:

Maximization of the buckling load

$$\max_{x \in \mathbb{R}^n} \left\{ f(x) \mid g(x) \geq 0 \right\} \tag{1}$$

$f(x)$	buckling load to be maximized,
x	design variable vector,
$g_1(x)$	given weight W,
$g_{1+i}(x)$	upper and lower bounds of the design variables.

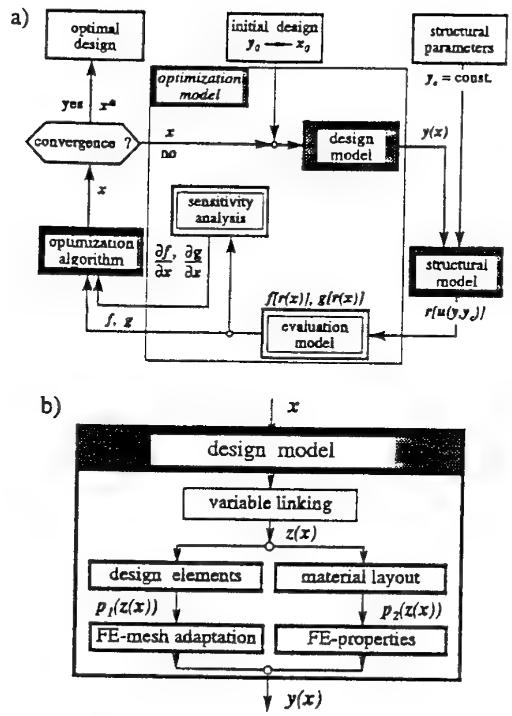

Fig. 11: Optimization loop

A fundamental solution procedure for general optimization problems - and thus also for Composite Structures - is presented by the "Three Columns-Concept" /ESC93, KRA93/. Fig. 11 schematically illustrates the division of the optimization task into the three main parts "structural model", "optimization model" and "optimization algorithms" in the form of an optimization loop.
As already mentioned above, an increase of the optimization efficiency of structures endangered by buckling, like the stiffened panel treated here, requires a correspondingly structured design model to be formulated prior to the actual realization of the optimization. The single steps of a "constructive design modeling" are presented in the Fig. 11. In the following, they shall be described in more detail.

3.2 Constructive design model

The design model describes due to Fig. 11 the relation between the design variables x and the variable parameters y of the analysis model required for the calculation of the component behaviour.
Within the design model at first a linear transformation is carried out by a so-called " variable linking ", where several analysis variables are assigned to one design variable:

$$z_j = a_{ij}\, x_i + z_j^{0} \tag{2}$$

$z_j,\, z_j^{0}$ j-th constructive variable, corresponding initial value ,
a_{ij} allocation matrix ,
x_i i-th design variable .

The suitable definition of the design variables represents an important aspect within the optimization task. The simplest method to be realized in the scope of a shape optimization of components is to use the parameters of the structural analysis model as design variables, for instance by defining the FE-nodal coordinates of a FE-model as design variables. This procedure however has some decisive disadvantages illustrated in /BRA83/. In the present case, the re-positioning of a stiffener would require a coupling of the components of the displacement vector ($\Delta\, x^k{}_i$) in order to secure the linkage between stiffener and base panel (Fig. 12a). In addition, the nodal displacements would have to be coupled to make sure that all nodes of the stiffener remain in the stiffener plane after the displacement. This procedure would thus not be useful for practical applications.
Therefore a more suitable approach should possess the following basic features:

- explicit coupling rules are unnecessary,
- reduction of parameters for the variation of the shape and the position of a stiffener element,
- constructive description of a component independent analysis model.

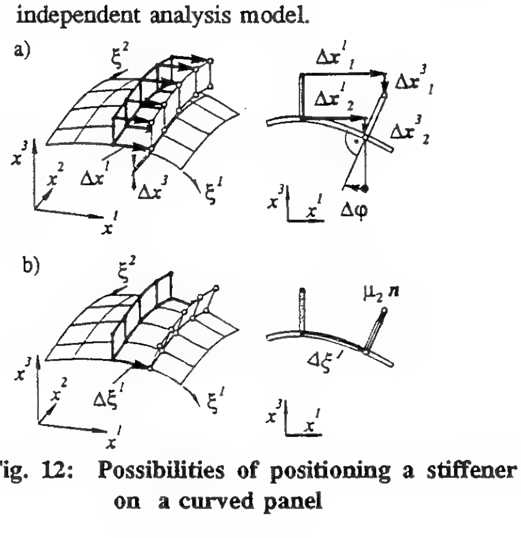

Fig. 12: Possibilities of positioning a stiffener on a curved panel

These features are included in so-called "constructive design models" (SCH95). Their fundamental constituents are the geometrical modeling of the constructive layout and the linking of the design variables x_i with the constructive variables z_i (like dimensions and position of the stiffener) instead of directly with the analysis variables of the analysis model. From the geometrical modeling by means of parametrical approach functions a parametrical description of the component can be obtained. During the optimization all variations of the component are performed in the parameterized model. This procedure allows to use both the coefficients (e.g. for a variation of the component shape) and the independent parameter of the approach functions as design variables. The latter facilitate a re-location of the design variables on a prescribed contour and is used in our case for the positioning of a stiffener on a given panel surface (12b). Based upon the constructive layout, the analysis variables y are then calculated for the different analysis models (11a). Since in the present case only smooth and relatively small variations of the geometry occur during optimization, the necessary FE-mesh adaption can be carried out by means of isoparametrical distortion rules /ZIE71/.
Proceeding from the fundamentals of the constructive design models, the following chapter shall intrude design models using design elements for stiffened panels.

3.3 Design elements concept

A suitable procedure for the shape optimization of structures is the design element method introduced by IMAM /IMA82/, where a structure is devided into simple sub-elements like lines, surfaces, ruled bodies, denoted design elements. These areas are defined by keypoints; each design element is described by corresponding shape functions and is controlled by so-called "master nodes". A geometrical modelling of this type is used in many CAGD-procedures /BLE90/. The master nodes to be varied during optimization are defined by a set of design variables.
For a plane structure the rule of interpolation within a design element can generally be given as follows:

$$r = r(x^k(\xi^\alpha)) = r(\xi^\alpha) = \sum_{i=0}^{m} \sum_{j=0}^{n} b_i^k(\xi^1)\, b_j^k(\xi^2)\, a_{ij}^k ;$$
$$(\xi^1, \xi^2) \in [0,1] \tag{3}$$

with x^k Cartesian coordinates, $k = 1,2,3$,
ξ^α independent surface parameters, $\alpha = 1,2$,
a_{ij}^k coefficients of the approach functions,
$b_i^k\; b_j^k$ parametrical approach functions .

In order to geometrically model the panel structures in this paper, section-wise defined bicubical BÉZIER-splines (patches), which are linked with each other C^2-steady, have proved to particularly suitable /SCH95/.

In order to formulate a stiffener design element, we require in addition to the position vector r (ξ^α) the tangential surfaces and the normal vectors. The combination and logical linking of surface elements allows for the definition of macroelements used for the geometrical modelling of stiffener elements. The position of a stiffener can then be determined via a position vector to the initial point r_{A1} and end point of the stiffener (see Fig. 13). The following equations yield the characteristical keypoints which defines the cross section of the stiffener:

- *lower flanges*

$$\mathbf{r}_{Bi}(\zeta^\alpha) = \mathbf{r}_{Ai}(\zeta^\alpha) + \mu_1 \Delta\zeta^\alpha_A \tag{4a}$$

- *blade height*

$$\mathbf{r}_{Ci}(\zeta^\alpha) = \mathbf{r}_{Ai}(\zeta^\alpha) + \mu_2 \mathbf{n}_{Ai}(\zeta^\alpha) \tag{4b}$$

- *upper flanges*

$$\mathbf{r}_{Di}(\zeta^\alpha) = \mathbf{r}_{Ai}(\zeta^\alpha)+\mu_2 \mathbf{n}_{Ai}(\zeta^\alpha)+\mu_3 \mathbf{n}_{Ci}(\zeta^\alpha) \tag{4c}$$

These ensure that the stiffener is always defined orthogonal on the base panel. The parameters used for variation of the shape are μ_1, μ_2, μ_3. By this manner, together with the vector r_{A1} only four different parameters are necessary to vary the position and the shape of a stiffener element.

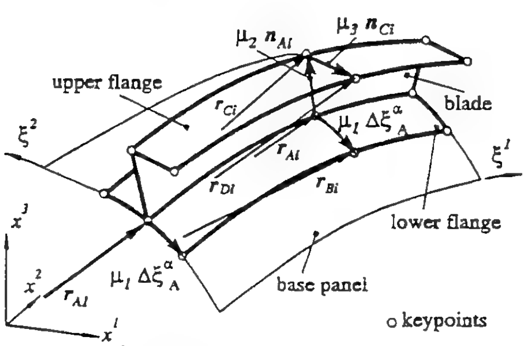

Fig. 13: Stiffener design element

3.4 Parametric description of the constructive layout

By means of a parametrical description of the panel base in the form (3) and 3D surface can be transformed into a 2D unit area, where the stiffeners form the boundaries of the single sub-surfaces. Thus, the position of a stiffener in the 2D plane is also determined and can be moved on the plane by means of the surface parameters ζ^α (Fig. 14). Explicity defined coupling relations for the displacement vectors as would be required in the 3-dimensional space are not necessary here.

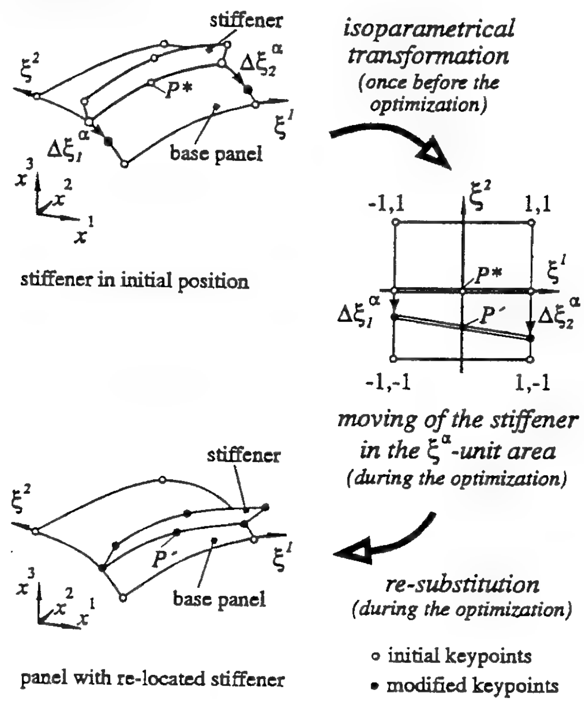

Fig. 14: Moving of a stiffener using design elements

For a transformation from the 3-dimensional space into the 2-dimensional plane, the parameters ζ^α for a given point r * (x^k) on the given surface are to be determined. Since for this transformation no explicit rule can be given, the surface parameters $\zeta^{\alpha*}$ for a given point r* (x^k) are calculated iteratively by means of a minimization of the distance.

3.5 Test example

The following test example shall illustrate the efficiency of the developed design models. For this purpose, a simply supported composite panel with

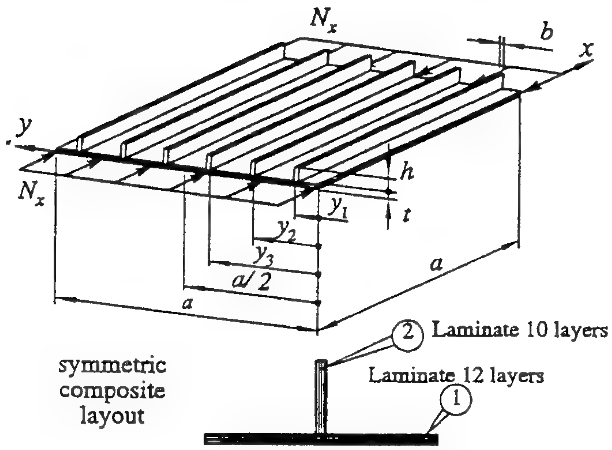

Fig. 15: Test panel to be optimized

six longitunal stiffeners is considered. It is subjected to an uni-axial load N_x (see Fig. 15). The material in the base panel is arranged in 12 and in the stiffeners in 10 symmetrical single layers. As design variables 11 parameters for the stiffener arrangement, the stiffener dimensions and the material layout in the stiffeners and the base panel are considered. The objective function the constraints for the example are defined according to (1).

Table 1: Definition of the design variables

Groups of Design Variables		Design Variables
Lam. 1	fiber orientations	$\alpha_1^{\,1}$
	ply thicknesses	$t_1^{\,1}, t_5^{\,1}, t_6^{\,1}$
Lam. 2	fiber orientations	$\alpha_1^{\,2}$
	ply thicknesses	$t_1^{\,2}, t_5^{\,2}$
positions; $y_i = \xi^2_{\;i}$		y_1, y_2, y_3
height: $h = \mu_2 \, h_0$		μ_2

Table 2: Definition of the variable-linking

	Variable-linking
Lam. 1	$\alpha_1^{\,1} = - \alpha_2^{\,1} = - \alpha_3^{\,1} = \alpha_4^{\,1}$
	$t_1^{\,1} = t_4^{\,1}$
Lam. 2	$\alpha_1^{\,2} = - \alpha_2^{\,2} = - \alpha_3^{\,2} = \alpha_4^{\,2}$
	$t_1^{\,2} = t_4$
positions:	$y_6 = a - y_1,\; y_5 = a - y_2,\; y_4 = a - y_3$

The buckling analysis using FE-method is based on the eigenvalue equation obtained from the second variation of the total potential.

$$(K + \lambda K_G)\, u = 0$$

with K ordinary stiffness matrix,
K_G geometrical stiffness matrix,
$\lambda = F_{crit} / F_{appl}$ eigenvalue,
u eigenvector.

This equation is solved numerically and yields the buckling eigenvalues λ_i which correspond to the ratio of the critical buckling load F_{crit} and the applied load F_{appl}.

Fig. 16 shows the results of the optimization calculations. We have used a SQP-algorithm according to POWELL/ SCHITTKOWSKI. It becomes obvious that the increase of the buckling load is caused by the enlargement of the stiffener elements by simultaneously reducing the wall thickness of the panels on the one hand. On the other hand, the increase is achieved by a substantial variation of the material layout of the base panel and the stiffener. In the optimum point, the buckling factors are very close to each other. Additionally it could also be stated that the buckling modes changes between local and global eigenmodes during the optimization process (Fig. 16). This fact shows that it is necessary to consider local and global buckling in an optimization process.

4. Conclusions

The framework SiFrame(R) has demonstrated that improvements in process control and data management can be achieved. This framework easily integrates existing UNIX based tools and makes teamwork and communication very transparent for the user. Question if SiFrame(R) is applicable as a framework to support the MDO process control has not been solved finally because of its lack of direct iteration options.

The implementation of a shape optimization methodology based on a constructive design model in the overall design process shows another way to come to an integrated design environment. Such design models describe the constructive layout of a structure depending on the design variables only. They are completely independent of the idealizations of the analysis models. Thus, they can be used in a multidisciplinary optimization process as a common basis for calculating the parameters of different analysis models.

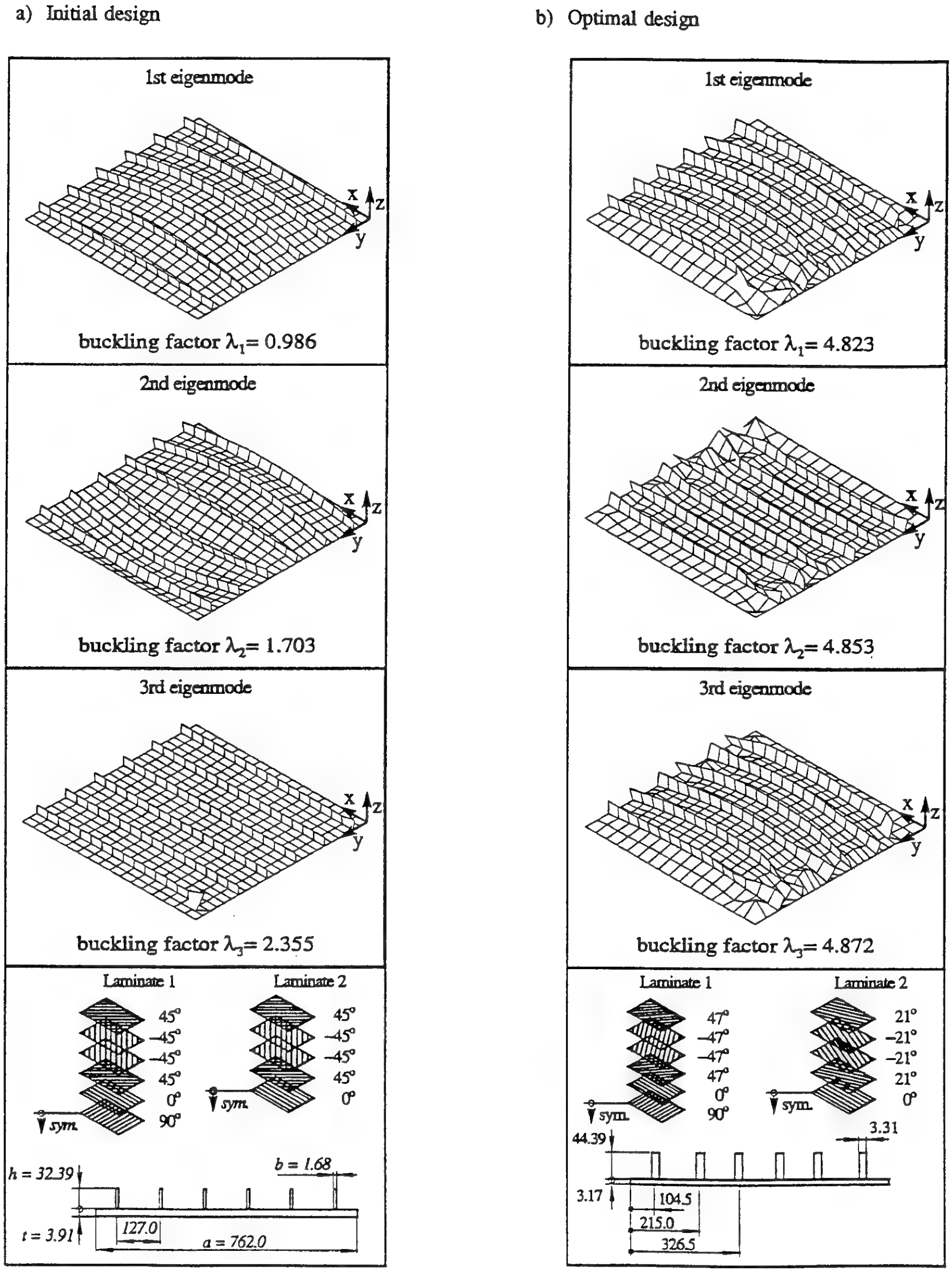

Fig. 16: Comparison between initial and optimal design

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INTEGRATED AIRFRAME DESIGN TECHNOLOGY

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ABSTRACT

Multi-disciplinary Design Optimisation (MDO) requires sensitivities and model data to be passed amongst many applications, such as FE and CFD codes.

Each iteration to the optimum design requires a re-execution of some of the applications, passing new input data and receiving updated sensitivities.

All this is happening within a backdrop of applications moving from a central mainframe to numerous Unix workstations. Therefore in order to perform MDO one has to solve problems of transferring data and executing remote applications.

One also requires most applications to be available during a lengthy optimisation process, which is demanding on the reliability of networks and computers. MDO can tackle this cheaper by building in redundancy.

This paper will outline our vision of MDO and detail our work and problems in performing:

* Remote application execution
* Data Transfer over local and wide networks.
* Network topology to give redundant data paths.
* Redundant computers via multiple application installations.
* Real-time interactive guidance of the optimisation process.
* Dynamically linking distributed applications to parallelise the optimisation process across workstations and supercomputers.

1. INTRODUCTION

The need to maintain a strict control on the total aircraft mass is a fundamental activity pursued in the Concept, Design and Production stages of an aircraft project. Similarly the structural integrity of the airframe has to be maintained in all these stages and confirmed in the qualification stage.

It was therefore not surprising that early single discipline optimisation activities were pursued within stress offices using simple stress ratioing techniques. Using this simple technique the amount of material at various locations could be determined such that a fully stressed situation existed under at least one loading condition. In some cases one could stretch the imagination to state that cost was being considered in that material cost could be directly related to the mass of a structure. However in most cases mass reduction investigations usually resulted in increased production costs. These were considered a necessary evil in the drive to reduced mass.

Single discipline (structural analysis) optimisation progressed to dual discipline when stiffness constraints began to emerge as the dominant constraints. The additional discipline being Aeroelastics - aeroelastic constraints were manipulated into simple displacement constraints which could be coupled with the previous stress based constraints and resolved using FE analysis techniques.

The manufacturing discipline could be considered to be represented by the application of minimum and maximum gauge

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constraints. More detailed manufacturing constraints were incorporated into optimisation systems with respect to structures made from Carbon Fibre Laminated Materials. These constraints were manipulated into maximum/minimum relative thickness distribution constraints for the different ply orientations.

Within BAe MAD Optimisation studies in relation to several other disciplines e.g. Performance, Vulnerability, Electromagnetics, Manufacturing either use resulting models from the Structural optimisation investigations or provide basic optimised configurations which were then sized considering structural and aeroelastic constraints.

Thus a system evolved which could automatically determine the minimum mass structure satisfying structural, aeroelastic and manufacturing constraints. However we are a long way from the realisation of a single automated system for multi-disciplinary multi-objective function optimisation. We first need to provide an environment which provides access to the various discipline's optimisation/analysis applications and can communicate with one another using standard data interfaces.

2 PREVIOUS ENVIRONMENT OVERVIEW

Figure 2.0 shows the complex hardware and software environment in which the Structural Optimisation process operated within MAD. Aerodynamic sensitivities in the form of Influence coefficients would be determined by applications working on an IBM mainframe. Structural FE models were formed in the DEC environment using PATRAN applied to geometry which could have been generated from a multitude of applications working on a mixture of DEC cluster and IBM mainframe. Aerodynamic pressure distributions generated on the IBM were transferred to the DEC where they were condensed onto the structural model using in-house software. Inertia loading was generated on DEC from a mass distribution data base system and subsequently distributed to the FE model using in-house software.

Thus an optimisation task would be formed in the DEC environment then submitted to the IBM mainframe for execution and subsequently post processed on DEC. This involved the transfer of huge amounts of data between DEC and IBM. The transmission rates were low in the order of kilobytes per second. This invariably resulted in a collapse of the interface leading to tasks either not being submitted to the IBM or an even worse situation where complete analysis results were lost!

The generation of FE geometry from CAD geometry used a combination of processes. For instance wing surfaces would be formed in PATRAN using digitised drawings. Out of plane ("Z") co-ordinates would be generated from in-house master geometry software and incorporated into FE models either using PATRAN or by manual editing of NASTRAN bulk data files. As stated previously in-house developed software was used to condense aerodynamic pressure loading data onto the FE models. In-house software was then used to check that the correct loading was being applied to the models and that the models had been idealised correctly.

Results from an analysis/optimisation were a mixture of character and binary data. These required translating from IBM to DEC internal formats before they could be post processed in the DEC environment. This was a simple process for character data. However binary data translation of floating point numbers required complex conversion routines. This additional work was considered an acceptable penalty in comparison to the huge increase in file sizes which resulted when all the analysis results were obtained in character form.

Graphical post processing was in the majority of cases performed using PATRAN. However where PATRAN did not provide a capability particularly with regard to composites, in-house systems were developed.

Thus a complex "integrated" environment evolved which was very difficult to maintain and invariable broke down.

3 INTERIM INTEGRATED SYSTEM

The long term vision for the integrated design environment was seen to revolve around supercomputing for analysis and distributed workstations for pre and post processing. However this would be an extremely costly exercise and coming at a time when we would struggle to finance the activity.

A CRAY supercomputer had already been acquired mainly for Computational Fluid Dynamics (CFD) work and links existed between it and the IBM environment. Aerodynamic applications providing data for structural analysis/optimisation were mainly performed in the IBM environment. The link to CATIA was seen to be a strategic item in the development of an integrated design environment and CATIA was then utilised on the IBM. The major problem with the analysis/optimisation environment described in the previous section was seen to be the link between the IBM and DEC. Therefore a strategic decision was made to migrate the pre and post processing associated with structural analysis from the DEC to the IBM.

Many of the graphical pre and post processing capabilities previously performed by in-house software were now available in PATRAN. Therefore the opportunity was taken to discontinue the use and maintenance of these systems. Also several detail stressing and mass accounting in-house software not directly linked to the analysis optimisation capability remained in the DEC environment. However new in-house post processing capabilities had to be developed in the IBM environment to satisfy the requirements of the Structural Health Monitoring process linked to FE analysis. Also the utilisation of Grid Point Force Balance data from FE analyses resulted in the development of a Graphical Capability which was not available within PATRAN.

Concurrent with this we began the migration of the automated optimisation system from the IBM to the CRAY. Which pointed the way towards the utilisation of NASTRAN on the BAe CRAY at Farnborough as opposed to the MAD IBM at Warton.

Thus an interim environment (figure 3.0) evolved which enabled us to support the continuous use of the analysis/ optimisation process, provide a stepping stone to our envisaged environment and produce reduced software licence and maintenance costs to MAD and BAe.

4 PRESENT/FUTURE ENVIRONMENT

A vision of the future hardware environment which will be utilised by structures people involved in Airframe Design is shown in fig 4.0. We are presently investigating the relative merits of the various desk top user interfaces.

The supercomputing installation involves both CRAY vector and massively parallel machines. Structural optimisation and analysis systems are at present only performed on the vector machine. The massively parallel machine being used for CFD codes and Electromagnetic analysis. However the utilisation of NASTRAN on the MPD will lead to a closer coupling of the all three disciplines with respect to design optimisation.

The supercomputing installation is located at BAe headquarters in Farnborough and is used by all BAe business units plus several external customers. Optimisations are executed remotely from Warton, Brough, Farnborough and Filton.

Models are stored locally and transmitted over the wide area network to the supercomputer, printed output is returned to the local network. The future aim in this case is to set up redundant paths such that if one link fails the data will be transmitted via another working path to the supercomputing centre.

Similarly multiple installations of the analysis/optimisation capabilities will be provided such that if the work load on the preferred supercomputing installation is too high then another installation could be utilised automatically. All of this being transparent to the user working in his local environment.

The present and proposed application software and data environments which are and will be utilised on the hardware described above are shown in figures 4.1 and 4.2.

At present NASTRAN results and restart data bases are stored on disks which are managed by a Convex super workstation acting as a file server. The machine also acting as super computer for several codes used by other BAe business units. The restart files remain on the fileserver's disks the results data output2/4 and X data bases are are transferred back to the local area networks were post processing is performed using PATRAN and or in-house developed systems (SOARDS and ARPL). PATRAN is presently utilised on both MVS and UNIX environments, however we will before the end of 1996 be fully migrated to PATRAN P3 on the UNIX environment. The SOARDS system presently used from the IBM mainframe is being migrated to the local unix environment. The ARPL system is also utilised on the IBM mainframe, however in this case it is being migrated to run on the remote CONVEX computer at Farnborough. Both of these systems process results data residing in the NASTRAN X data base. When the above migration is complete this data base can remain at Farnborough and be accessed remotely by SOARDS and locally by ARPL.

In the proposed future applications environment as shown in figure 4.2 the SOARDS and ARPL capabilities need to be made available in either PATRAN or NASTRAN A closer coupling of NASTRAN and PATRAN is envisaged resulting in a reduction of the number of data bases associated with their use. However the data base associated with PATRAN will need to operate more efficiently in client/server mode.

FE based optimisation needs to be coupled much more efficiently to the NASTRAN than it presently is in the ECLIPSE system. Detail Stressing modules developed in the local environment need to be developed such that they can be rapidly incorporated into the optimisation capability. We are at present investigating Object Oriented approach to software development as a means of fulfilling this requirement.

Automated links to the real structure geometry are essential in an integrated environment. However the level of capability required by the design engineer and structural engineer varies. We are continuously investigating the performance of the various hardware/software environments which can be used to access and manipulate the geometry. In performing this activity the level of skill of the people involved increases along with their requirements. Therefore the hardware provided needs to have growth potential to satisfy the increasing demands. Thus we are finding that in a concurrent engineering team the majority of desk top devices used by the structural engineer should be X terminals with strategically located desk top workstations.

PC based software has become an essential requirement for the structural engineer. In certain cases it is all they require to do their work. It is not only the provision of user friendly word processing, and presentation capabilities but graphical mathematical libraries providing detail stressing capabilities are available. By providing access to these facilities from an X terminal coupled to a PC application server with the user data NFS mounted on a Unix file server the structural engineer may access all of the software applications he is likely to require. All of the applications are accessed via a user interface which removes the requirement for the user to decide which machine they need for which application. This also removes the user need to know where the data is stored yet provide the flexibility for them to manage, change and manipulate model data generated and imported from external sources.

The user interface will also be the means of providing real time interactive guidance on the design optimisation process. Knowledge based tutorial and help systems need to be incorporated with all applications.

Once all the applications are made available the process of dynamically linking all of them to parallelise the optimisation across the distribution of workstations, supercomputers and PCs can begin.

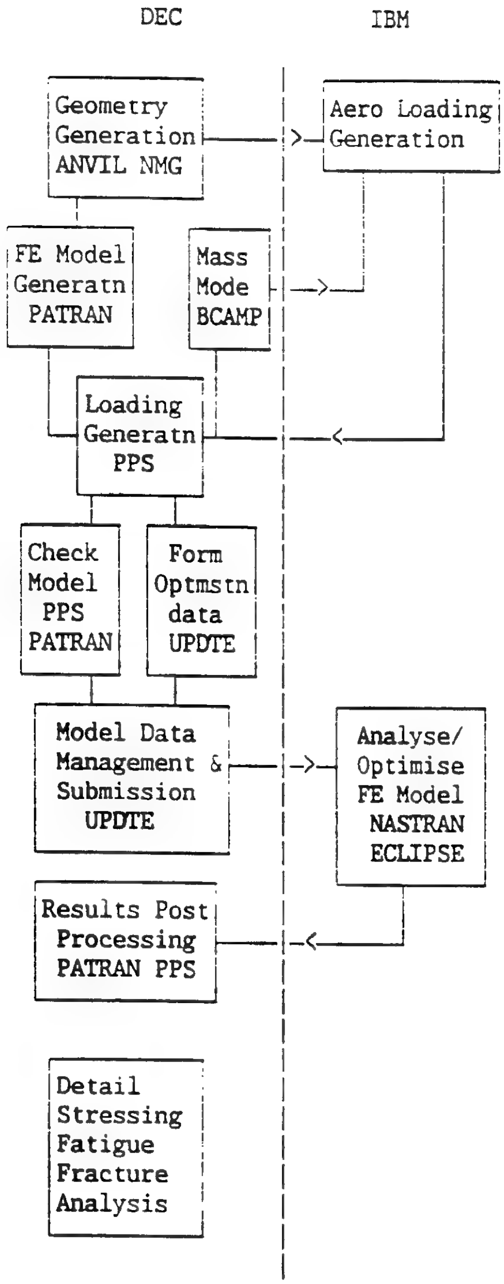
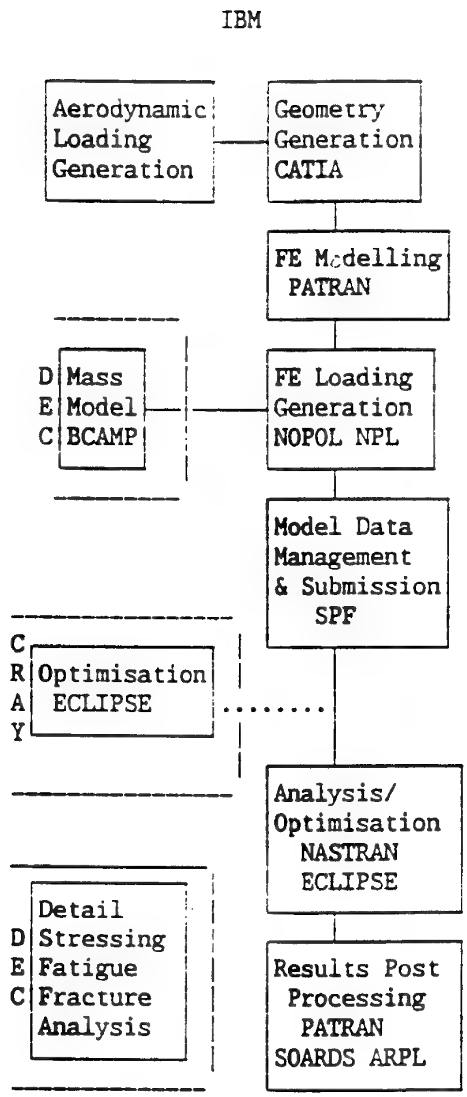

DEC
IBM
Geometry Generation ANVIL NMG
Aero Loading Generation
FE Model Generatn PATRAN
Mass Mode BCAMP
Loading Generatn PPS
Check Model PPS PATRAN
Form Optmstn data UPDTE
Model Data Management & Submission UPDTE
Analyse/ Optimise FE Model NASTRAN ECLIPSE
Results Post Processing PATRAN PPS
Detail Stressing Fatigue Fracture Analysis

Fig. 2.0


IBM
Aerodynamic Loading Generation
Geometry Generation CATIA
FE Modelling PATRAN
DEC
Mass Model BCAMP
FE Loading Generation NOPOL NPL
Model Data Management & Submission SPF
CRAY
Optimisation ECLIPSE
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DEC
Detail Stressing Fatigue Fracture Analysis
Results Post Processing PATRAN SOARDS ARPL

Fig. 3.0

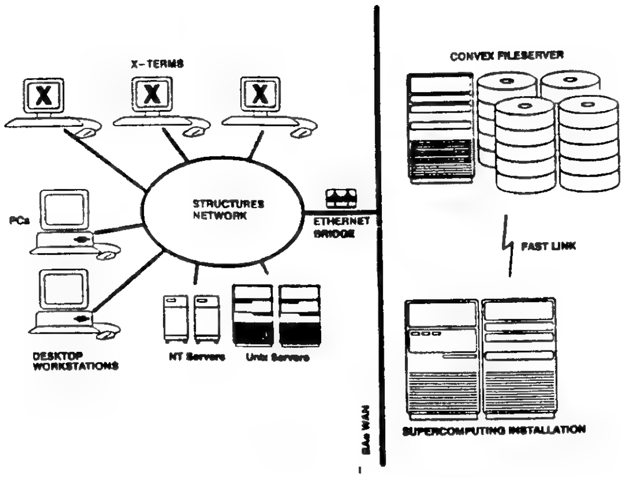

Fig 4.0

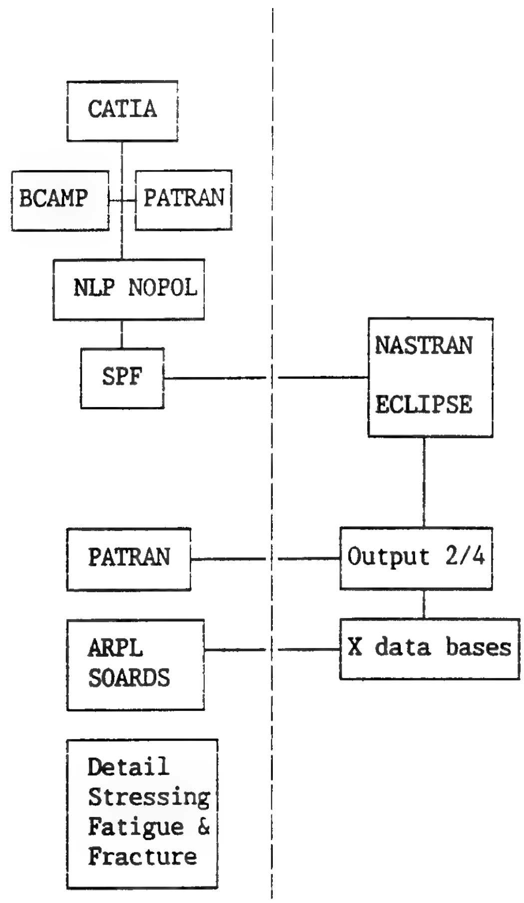

Fig 4.1

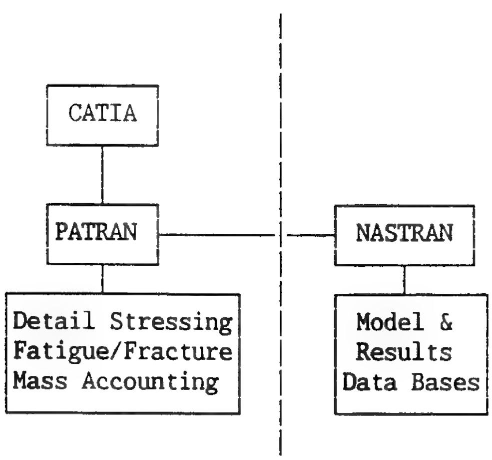

Fig. 4.2

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A MULTIDISCIPLINARY APPROACH IN COMPUTER AIDED ENGINEERING

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1. SUMMARY

Computer Aided Engineering (CAE) has a long history within Fokker. Already in 1955 the FERTA-computer (Fokkers Eerste Rekenapparaat Type Arra) was used for aeroelastic analysis of the F27. Many disciplines automated their design methods in the sixties and seventies. The resulting islands of automation started to be recognised as a problem only after some time.

Fokker Aircraft had come to a stage where significant progress could only be achieved by integrating the various disciplines and their CAE-models. These models should be applied in support of a properly designed process. Therefore the CAE-project was started in 1994. During this project a transition was made from "each specialist building his own CAE-model" towards teamwork in building multidisciplinary CAE-models.

This will be illustrated by a number of examples from area's like weight & balance, flight dynamics and structural design & optimisation. Finally, a view of future developments is presented, building on the historical perspective of CAE developments at Fokker Aircraft.

2. INTRODUCTION

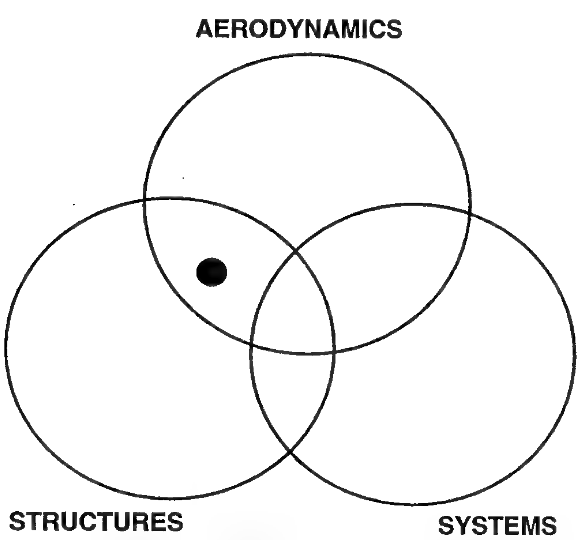


Fig. 1: functional area's in which CAE-models are used. The position of the first CAE-application in 1955 (aeroelasticity) is indicated as a black spot.

The arena in which CAE-models are applied can roughly be divided in three functional area's with a considerable overlap:

- AERODYNAMICS, delivering the aircraft external shape.
- STRUCTURES, delivering the aircraft structure.
- SYSTEMS, delivering (among other systems) the aircraft control system .

In 1976, when the first "engineer friendly" DEC10 computer arrived at Fokker, almost every discipline started to automate its design methods to a considerable degree. The problems that had to be solved were primarily mathematical and numerical model formulation on one side and computer capacity on the other side. This effort was generally uncoordinated resulting in islands of modelling and automation. In those days this was not felt as a problem because of the clear benefit of speeding up and increasing the quality of the local processes. Fig. 2 shows the resulting area population with CAE-tools in 1980.

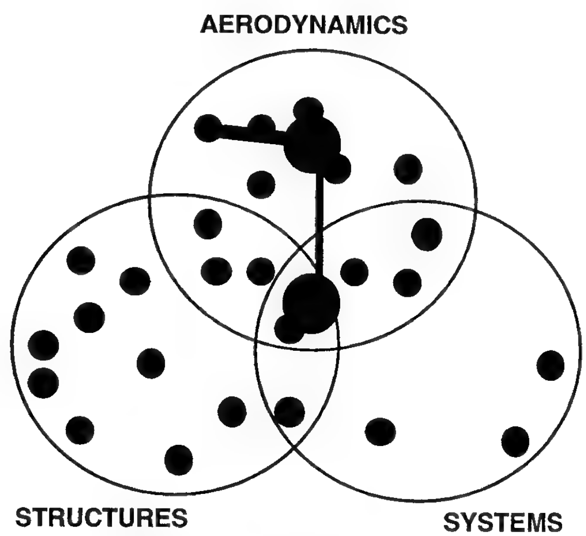


Fig. 2: the population of the three functional area's with CAE-tools in 1980. Various islands of automation had been created. The first attemps were made to create integrated design systems and connections between islands.

It was concluded that the islands, although successful and comprehensible, also had their drawbacks (see ref. 1):

- it resulted in time-consuming "translations" of data.
- models were different in many details, obscuring the necessary communication.
- consequently methods for estimating for example mass, aerodynamics and stiffness were too slow.

The goal of modern aircraft design is to optimise the total aircraft rather than the individual components.

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

Achievement of this goal requires a close co-operation between all disciplines influencing the design. Consequently it was concluded that Fokker Aircraft had come to a stage where significant progress could only be achieved by integrating the various disciplines and their CAE-models. These models should be applied in support of a properly designed process. Thus CAE follows the same route as CAD where the real strength of 3D modelling only came available when applied in support of processes that took advantage of 3D modelling, like digital preassembly and concurrent engineering.

3. THE CAE-PROJECT

The CAE-project started in 1994. The objective was to fill the gap between conceptual design and full scale development with appropriate tools to support the design feasibility phase and design definition phase (see fig. 3). Design iterations should be performed in these early design phases instead of during full scale development, supporting a "first time right" design process. This reflects the changing role of the Aircraft Design Organisation: their role is shifting from full scale development work towards the specification oriented first design phases.

The following aspects were felt to be of prime importance in the CAE-project:

- Integration of the conceptual design phase (where mostly semi-empirical CAE-tools are used) with the design feasibility phase, where more in-depth CAE-tools like Computational Fluid Dynamics (CFD) and Finite Element Modelling (FEM) are used. This allows for a quick response of the various specialist disciplines to the conceptual design.
- Integration of the specialist disciplines. During the CAE-project a transition was made from "each specialist building his own CAE-model" towards teamwork in building multidisciplinary CAE-models.
- Integration with the main 3D modelling system at Fokker (CATIA).

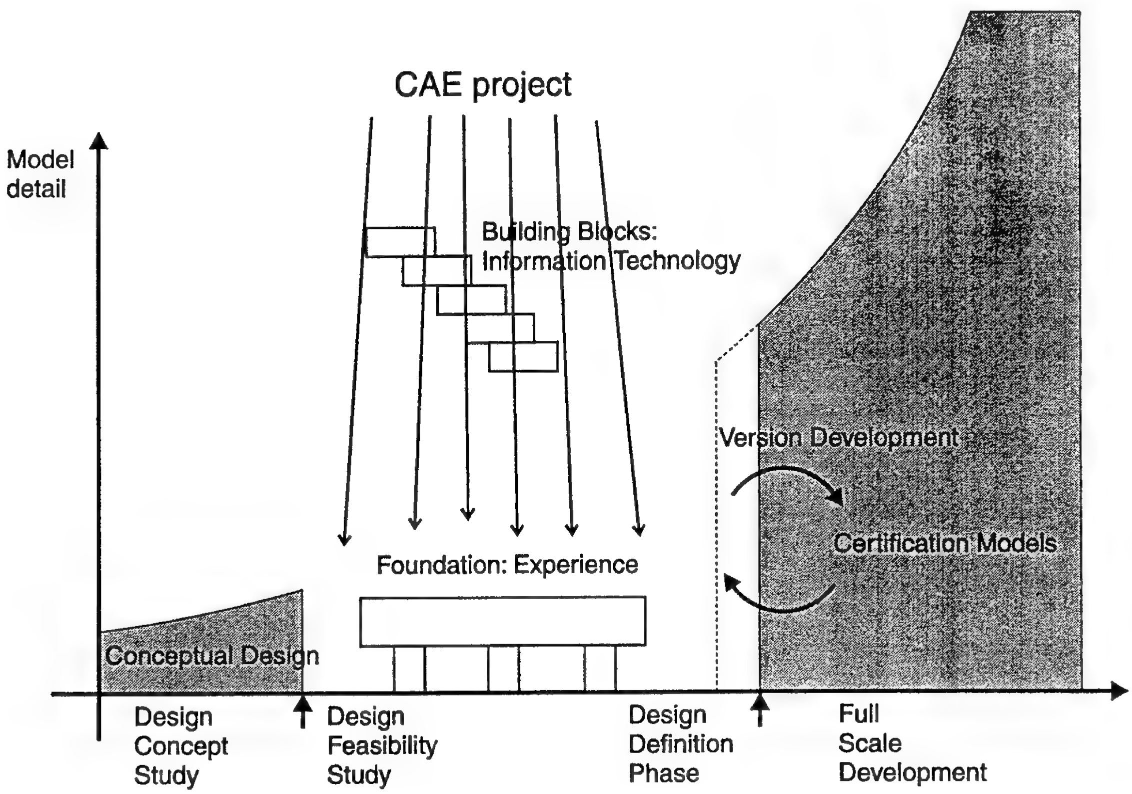


Fig. 3: the CAE-project was directed towards tool- and process development to support the early design phases of a Future Aircraft (FA-X). The experience gained in developing the F27, F28, Fo50, Fo100 and its derivatives provided the project with a solid foundation .

Fig. 4 shows the effect of the CAE-project on the population of the functional area's.

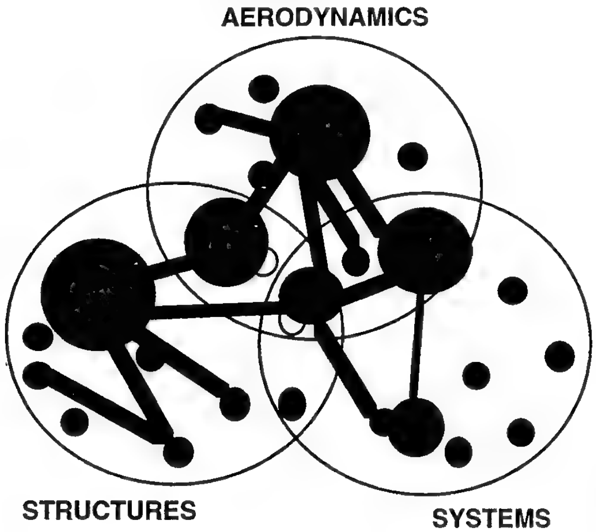


Fig. 4: the population of the three functional area's with CAE-tools in 1996. The CAE-project resulted in more integrated design systems and more connections between the various area's.

Analysis oriented disciplines should be placed as close as possible to the design process. This creates the opportunity for these disciplines to influence the design in an early phase (from analysis towards design optimisation). This has already been the case for many years in the area AERODYNAMICS where the application of CFD has become an essential element in the aerodynamic design process (fig. 5).

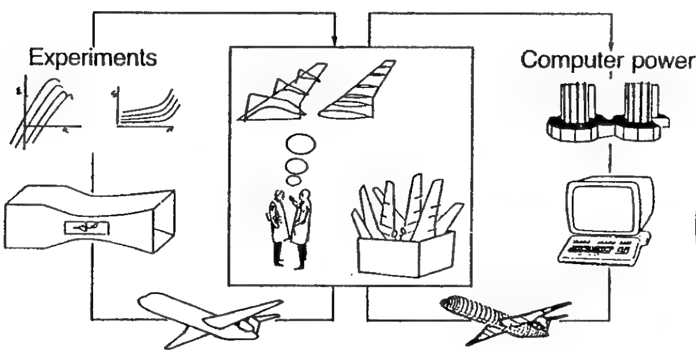


Fig. 5: for many years already computational fluid dynamics is an integral part of the aerodynamic design process.

However, the situation had to be improved in the SYSTEMS and STRUCTURES area : disciplines like aircraft loads and aeroelasticity tended to gather the necessary design information, build their own models and start the analysis. By the time their work had finished the possibility to influence the design had become very limited. Thus it was important to place these disciplines as close as possible to the <u>design systems</u> where for instance the aircraft control system or the aircraft structure is defined.

Developing a multidisciplinary CAE-process is not only about tool development but even more about developing the skill to work together effectively. Therefore in 1995 six design exercises were organised applying the newly developed processes and tools in the following fields:

- weight & balance.
- aeroelasticity.
- flight dynamics.
- loads.
- structural design & optimisation.
- powerplant specification & integration.

The design exercises were executed by multidisciplinary teams of 6 to 8 specialists and lasted for 8 to 12 weeks, using one of the FA-X (Future Aircraft) concepts as a carrier. These exercises proved to be very successful. Not only quite some misunderstandings were revealed, but also (the results of) the exercises generated a lot of enthusiasm among the team members as well as among their management. At the end of each exercise the results were presented within the engineering community.

The aspects and approach mentioned above will be illustrated in the next chapters by a number of examples from the following area's:

- weight & balance (chapter 4).
- flight dynamics, the influence of loads aspects on the aircraft control system (chapter 5).
- structural design & optimisation, the influence of aeroelastic constraints (chapter 6).

4. WEIGHT & BALANCE

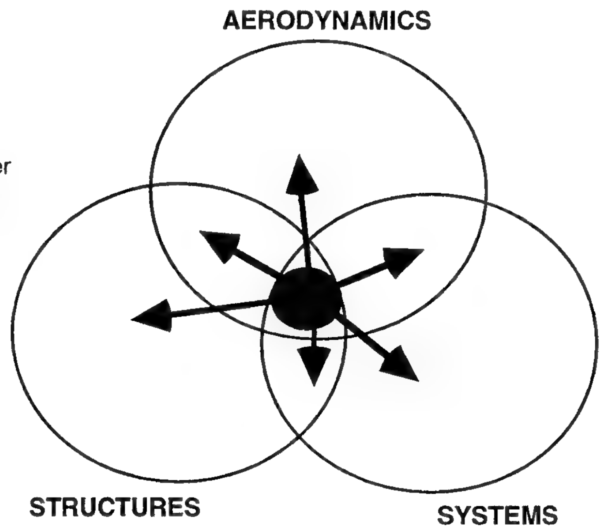


Fig. 6: position of weight & balance

Many disciplines require mass-data for their analysis, like stability & control, aeroelastics and loads. Mass-data in various stowing conditions is needed, varying the amount or position of payload and fuel. There used to be various models and tools for generating mass-data, each discipline more or less duplicating work of others. This could result in lengthy discussions about which model produced the correct data.

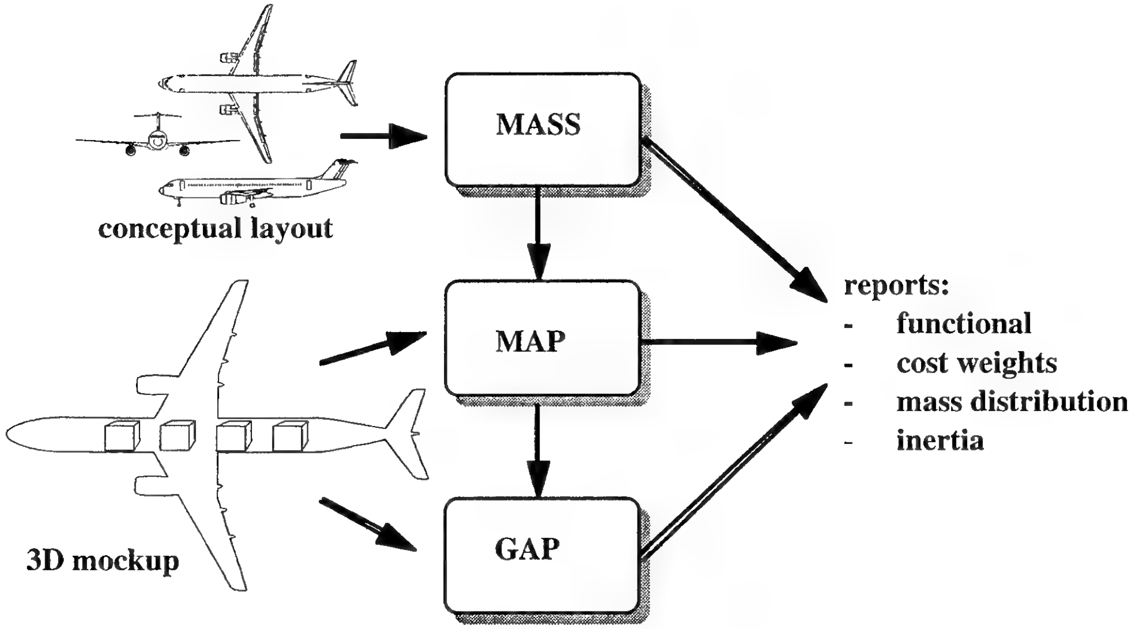


Fig. 7: tools for reporting the mass-breakdown from conceptual design (MASS) down to certification (GAP)

4.1. Process description

Within the CAE-project the following process was developed (see fig. 7). Three tools are used for the various design phases:

- MASS (used during conceptual design and feasibility study): a semi-empirical tool for mass-estimation using a conceptual description of the overall aircraft.
- MAP (used during the design definition phase and full scale development): Mass Allocation Program, uses more detailed design information of the individual aircraft components. MAP keeps track of the history of mass estimates, targets and budgets during the project.
- GAP (used during the certification phase and in version development): Gewichten Administratie Programma, uses detailed drawing information.

The tools are interfaced, i.e. MAP uses the MASS-data as starting point and GAP uses the MAP-data. Each identified aircraft part is contained in a box (mass-item), with position, dimensions and mass-distribution defined. MAP and GAP have been interfaced with the 3D electronic mock-up in CATIA. Thus, position, dimensions and mass-properties of aircraft parts can be directly retrieved from the most actual design information.

All three tools produce the same kind of mass distribution report, although the GAP-reports contain much more mass-items than for instance the MASS-reports (some 40.000 for GAP compared to 250 for MASS). The mass distribution report is used by all disciplines for adding fuel and payload using one harmonised model and tool.

Various methods are available to map the mass-data on a computational model.

- mass distribution over a beam model used for loads and aeroelastic calculations (see fig. 9).
- mass distribution over a FE-model used for multi-disciplinary structural optimisation (see chapter 6).
- totalled mass data, i.e. cg, moments of inertia. This data is used by stability & control specialists and is fully compatible with the mass distributions (see chapter 5).

4.2. Design exercise

One of the FA-X (Future Aircraft) concepts was used to exercise the new weight & balance process. Fig. 8 shows the mass-item representation of the FA-X, produced by the MASS-tool during conceptual design. Fig. 9 shows the mapping of the mass-item representation on a loads beam model.

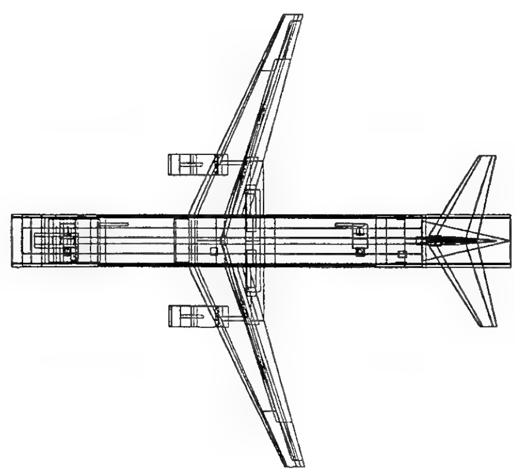


Fig. 8: electronic mass-distribution representation of the FA-X aircraft. The model contains approximately 250 mass-items.

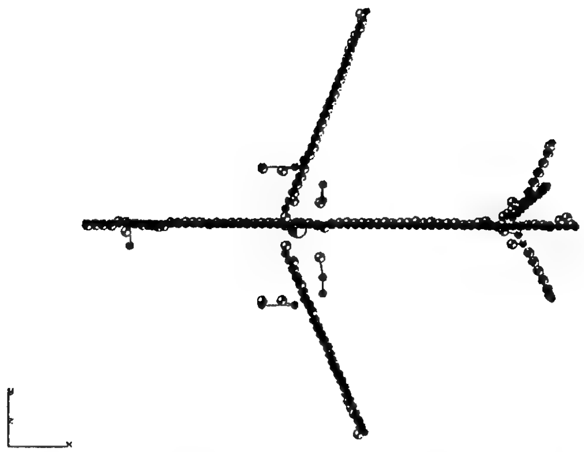


Fig. 9: mapping of mass-distribution on a beam model used for calculation of load distributions.

The mass-data was used for weight & balance studies to define the cg-limits necessary to accommodate all required payloads. The required cg-limits + payload / fuel model were used by the other specialists to generate various mass-distributions for their analysis: forward cg with minimum / maximum moment of inertia, aft cg etc. The definition of the cg-limits requires a multidisciplinary trade-off between weight & balance and specialists from stability & control, loads, aeroelastics etc. In the new situation this process was no longer obscured by lengthy and unproductive discussions about differences in model details.

5. FLIGHT DYNAMICS

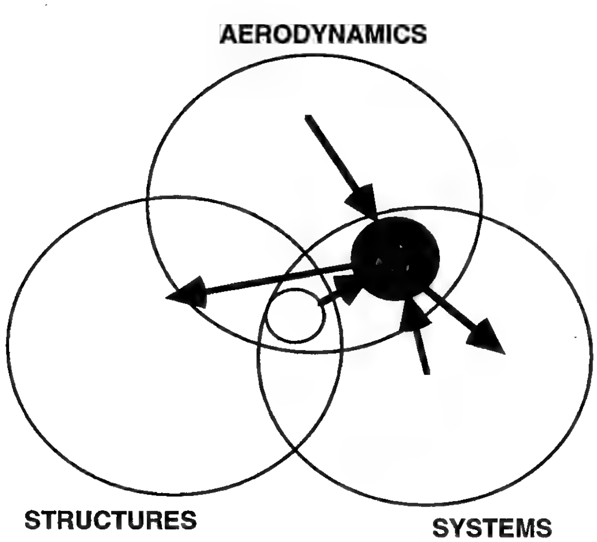


Fig. 10: position of flight dynamics

This chapter concerns the interaction of gust and manoeuvre loads with the flight control system. The loads definition is a complex process in aircraft design. Loads are influenced by almost every aspect of the design (e.g. aerodynamic data, mass and stiffness data, systems characteristics). Most aircraft structures are dictated by strength rather than stiffness requirements. So it is clear that the quality of loads predictions has a major impact on the quality of the result of the structural optimisation process. During the CAE-project various improvements were introduced in the loads definition process, with respect to landing-, gust- and manoeuvre-loads.

5.1. Process description

Various disciplines used to have their own simulation-tool for aircraft manoeuvres, for instance for stability & control, control law development and loads manoeuvres. Again, this considerably obstructed an effective co-operation. When for instance a control law developed by the systems specialist had to be analysed by the loads specialist, the control law first had to be implemented in the loads simulation-tool. This extra implementation work was the smallest problem however, worse was the discussions that might arise from the change in simulation environment. Control law issues were mixed up with discussions about differences in modelling for instance aerodynamics or mass.

An improved approach was defined in which each discipline provides sub model data concerning his expertise to a central simulation tool, thus using the sub models (and expertise!) of other disciplines. The Matlab/Simulink software was chosen as modelling / simulation / analysis environment. A generic aircraft simulation model was defined. The model has standard six degrees of freedom (rigid body motion) but can be extended with elastic degrees of freedom if necessary for certain applications (the corresponding mode shapes are computed using a NASTRAN FE-model, see chapter 6).

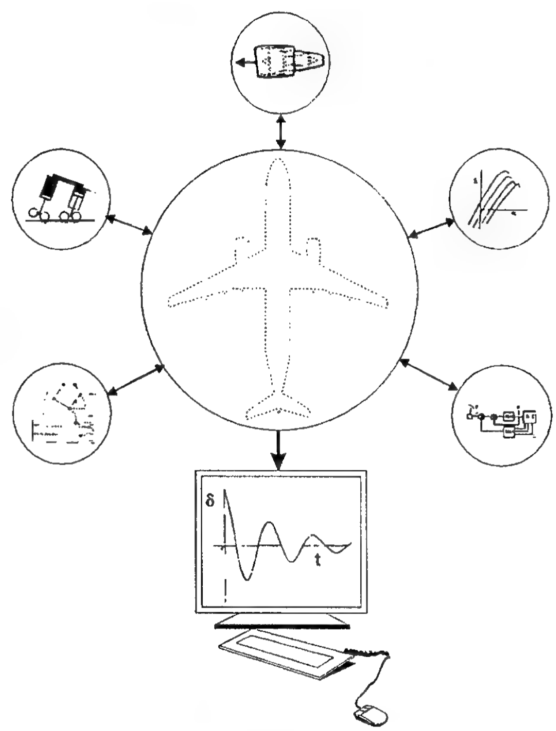


Fig. 11: this picture symbolises the aircraft simulation environment (CAE mock-up), showing modules for mass, landing gear, engine, aerodynamics and control system. The actual model is a Simulink schema, which combines matlab-functions, proprietary fortran-routines, and data-files for the aircraft under investigation.

Procedures and tools were developed to be able to quickly provide the generic aircraft simulation model with data for a specific aircraft, i.e. mass data, landing gear data, engine data, aerodynamic data and systems data. The simulation environment is supported with appropriate tools for configuration control, which is an essential ingredient in a multidisciplinary / multi user environment.

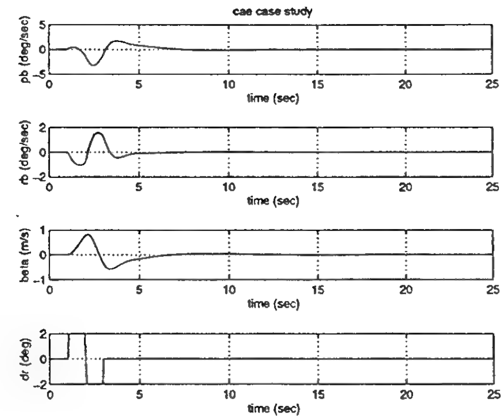
As mentioned in the previous chapter, the mass data was already harmonised between the various disciplines. An other important input for the aircraft simulation environment is the aerodynamic database, describing the aerodynamic forces acting on the aercraft as a function of various state variables. Again, the aerodynamic coefficients had to be harmonised between the conceptual design group, the aerodynamics group and other specialists using aerodynamic data.

A semi-empirical tool, EV-AERO, is used during conceptual design to provide a first estimate of aerodynamic coefficients and aerodynamic lift and moment distributions. The aerodynamic database derived from EV-AERO will be updated by an aerodynamics specialist in a later phase, on the basis of previous experience using scaling rules or using windtunnel data combined with CFD-calculations.

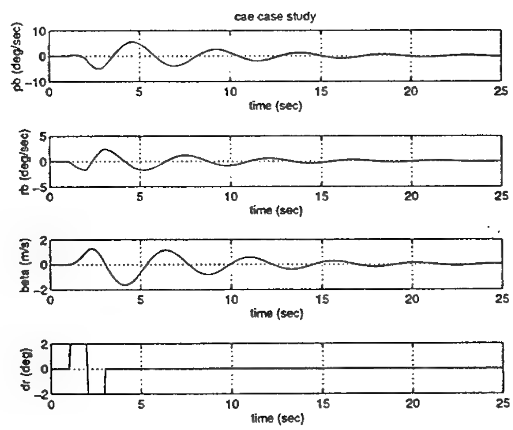
5.2. Design exercise

Again one of the FA-X concepts was used to exercise the new flight dynamics process. Specialists from stability & control, systems and loads demonstrated the multidisciplinary use of the simulation environment. The aerodynamic data of the FA-X was contained in the aerodynamic module of the aircraft simulation model. A stability & control specialist analysed the Dutch roll behaviour, using a rudder deflection to trigger the aircraft. The simulation model produced the resulting aircraft response. From the results of the Dutch-roll investigation, it was concluded that for passenger comfort a yaw damper was necessary to add extra artificial damping. A yaw damper control law was developed by the stability & control specialist in co-operation with the systems specialist.

Fig. 12 shows the aircraft response to the rudder deflection with and without yaw damper.



aircraft response with yaw damper

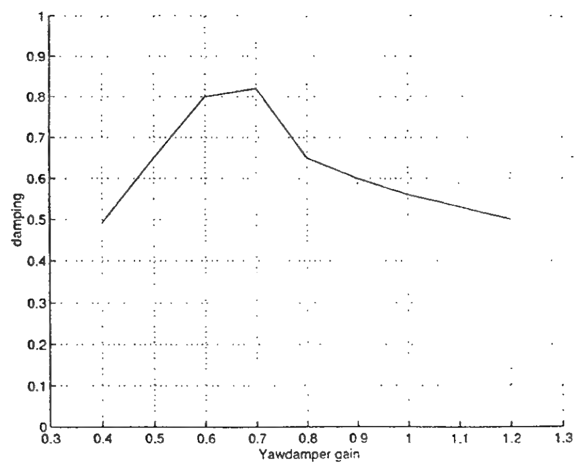


aircraft response without yaw damper

Fig. 12: influence of yaw damper on the aircraft response to a rudder deflection.

As a further step a number of loads cases were investigated by the aircraft loads specialist to analyse the effect of the yaw damper on the fin loads. The influence of the yaw damper on the fin loads strongly depends on the yaw damper gain (fig. 13).

For this exercise it was conclude that for flight handling a gain of .7 would be optimal while a gain of 1.2 would give minimum fin loads. The discussion is directly focused on this multidisciplinary trade-off that has to be made, because both specialists work together in the same simulation environment.



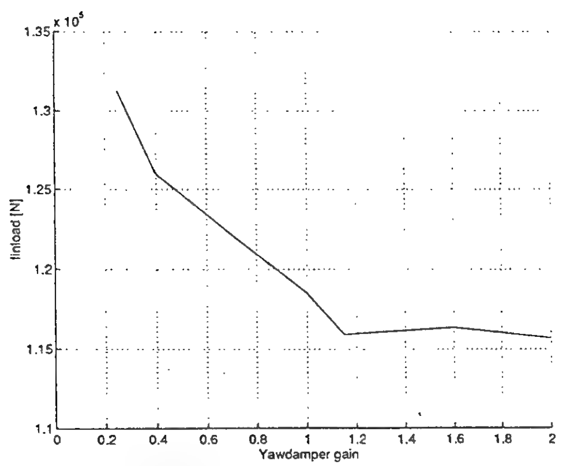


Fig. 13: damping and fin loads as a function of yaw damper gain .

6. STRUCTURAL DESIGN & OPTIMISATION

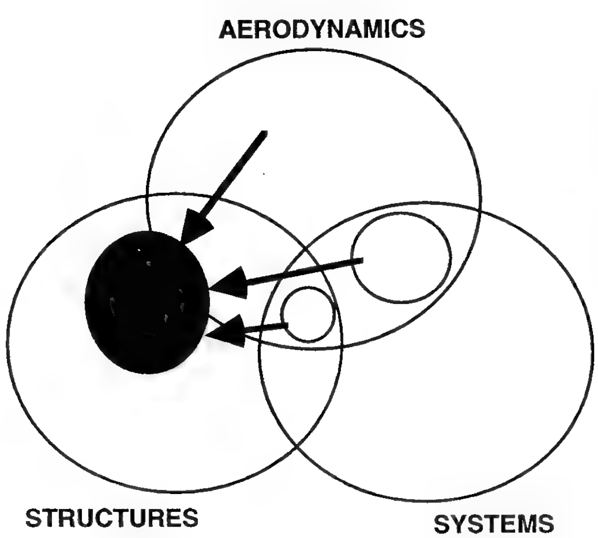


Fig. 14: position of structural design & optimisation

This example concerns multidisciplinary structural design & optimisation. Important inputs are geometry, aircraft loads, mass distributions and aerodynamic data. The central tool used for modelling and optimisation is MSC/NASTRAN (ref. 2).

6.1. Process description

The MASS program mentioned in chapter 4 is used during conceptual design to generate first estimates of mass, stiffness and loads. It uses a simple structural model. A simple aeroelastic beam model can be generated very quickly from the conceptual design information. The beam model is completed with a doublet lattice model to represent aerodynamics. It can be used for a first aeroelastic analysis of the design.

It is necessary however to set-up a much more detailed FE-model for structural design & optimisation. As a first step the external geometric shape is provided in the 3D modelling system CATIA. Also the basic elements in the structural concept, like wing-box, main frames, crash beams are defined in CATIA. This information is transferred to PATRAN using the CATPAT interface. Procedures have been developed in PATRAN to support generation of the NASTRAN analysis and design model.

To enable multidisciplinary use of the model, it is important to pay attention to a correct modelling of stiffness. Within Fokker the FE-models used to be developed for strength purposes only. In the CAE-project modelling rules were developed, resulting in a correct representation of stiffness. In this way the model can also be used for aeroelastic applications.

6.2. Design exercise

Again one of the FA-X concepts was used to exercise the new structural design & optimisation process. The FA-X structural model is made up of two parts: an analysis model and a design model (object function, design variables and constraints).

The analysis model:

A detailed FE-model of the composite wing box + wing-fuselage connection was developed, using the new modelling rules. Fig. 15 shows the resulting FE-grid of the wing box. For dynamic aeroelastic analysis the mass modelling, aerodynamic modelling and front / rear fuselage modelling were taken from the aeroelastic beam model. The dynamic solutions were computed on a reduced solution set to reduce the computational labour.

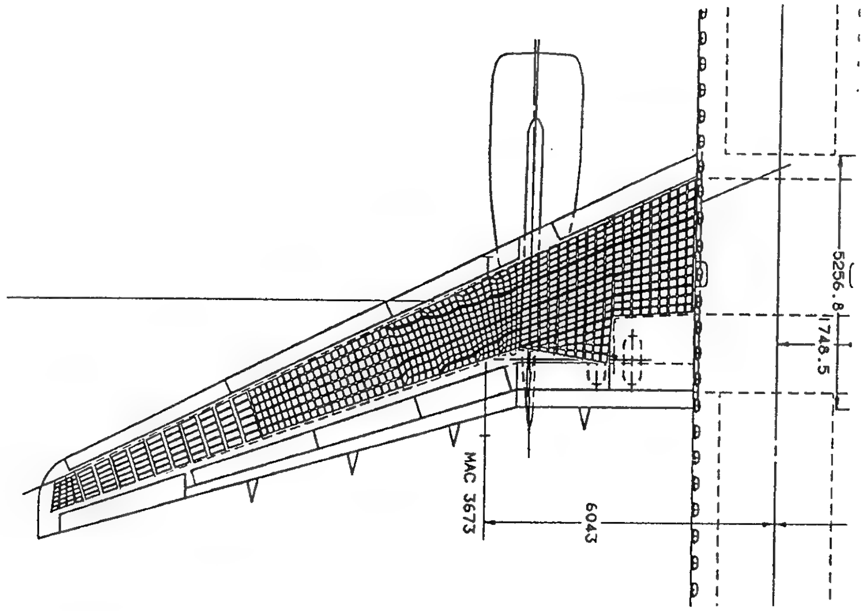


Fig. 15: FE -model of the FA-X composite wing box. The wing box has approximately 13.000 DOF's:

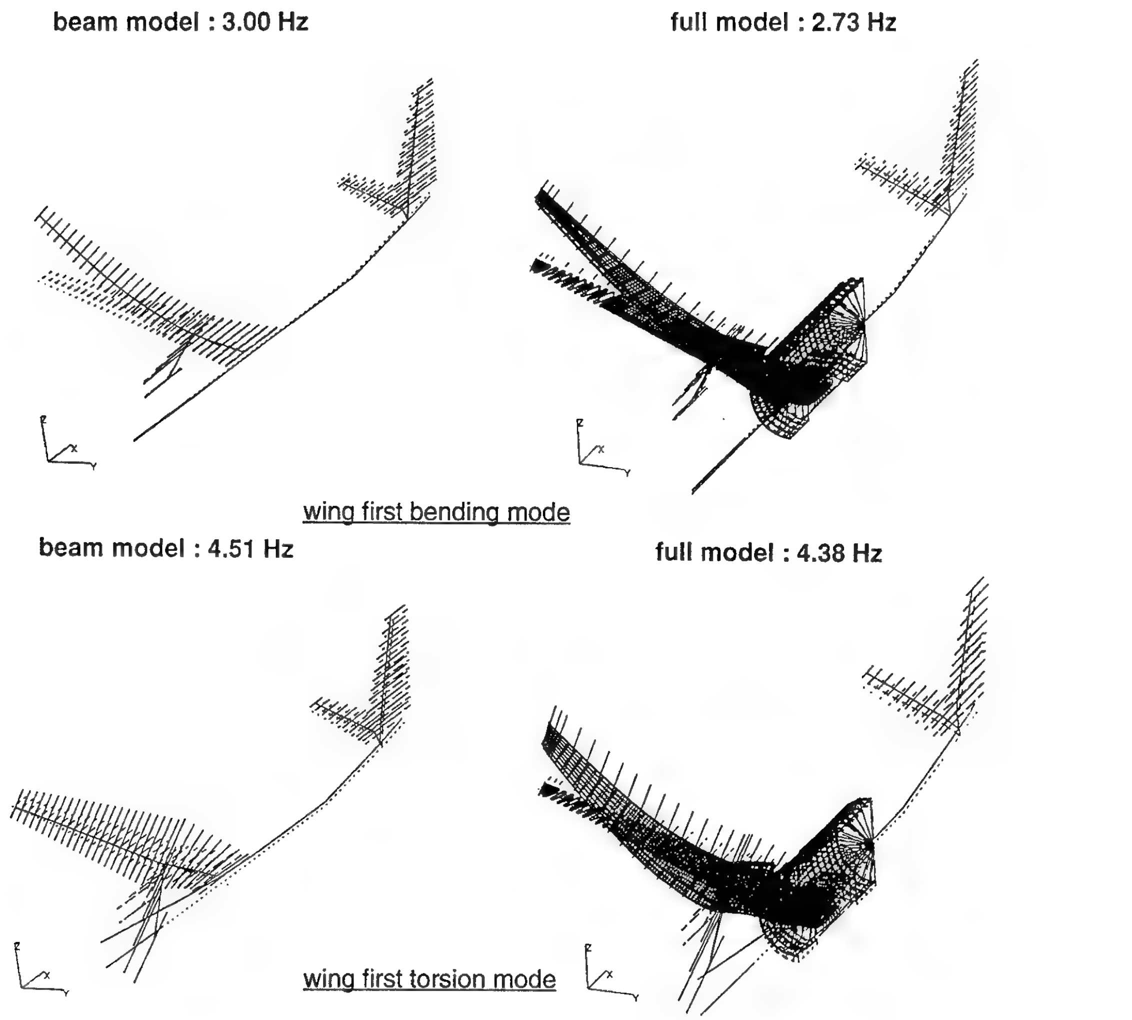


Fig. 16: comparison of mode shapes calculated with the simple beam model and the complete FE-model.

Design model:

- object function is minimisation of mass
- design variables are skin thickness and effective stringer thickness for both lower and upper skin panels. The design variables are distributed span wise and chord wise (inner wing region only). A total of approximately 300 design variables is used.
- constraints are allowable stress / strain and buckling. Panel efficiency curves were used which define the relationship between load index and structural efficiency, each curve representing a family of panels with a given skin / stringer ratio. Various aeroelastic constraints were used like maximum allowed deformation and flutter speed.

The aeroelastic beam model and the complete FE-model including wing-fuselage connection and front / rear fuselage are shown in fig. 16. It shows a comparison of the first bending mode and the first torsion mode of both models. The bending mode is in reasonable agreement. The torsion mode is clearly different, probably because the inner wing torsional stiffness of the complete FE-model is considerably larger than estimated by the MASS preliminary design tool .

Various optimisation and analysis runs were conducted. It was concluded that aileron effectivity was the most serious problem. This problem can be solved in various ways, one of them being the application of skin panels with increased torsional stiffness that are structurally slightly less efficient (as was already shown in ref. 3). Because the aeroelastic specialist is working in close co-operation with the structural designer on the same model, an effective trade-off can be made between structural efficiency and aeroelastic considerations. In the island situation the aeroelastic input would probably have come too late to make any adjustments to the design.

7. FUTURE DEVELOPMENTS

"in order to achieve economically viable high-performance aircraft of the future, an Integrated Aircraft Design (IAD) process is required. Integrated airframe design embraces the concept of bringing together all of the aspects of airframe design, including various disciplines such as structures, materials, aerodynamics, propulsion, systems, controls and manufacturing from conceptual design all the way to the final product and its repair and maintenance"

This statement has been taken from the Call for Papers for the AGARD workshop on Integrated Airframe Design Technology. The objective of the workshop is to recommend future R&D directions in IAD technology. This chapter is meant as a contribution to answering this question.

Computer Aided Engineering has come a long way since its first application within Fokker in 1955. CAE has become an essential element in the aircraft design process. Still we have only made the first steps towards an IAD process. A natural growth path is from isolated solutions towards integrated systems. Future developments will show continued integration of CAE-tools in multidisciplinary design processes. Two examples will be discussed in the next two paragraphs.

7.1. Further development of MDO-processes

This first example concerns the multidisciplinary optimisation of a wing. State of the art in aircraft design is that first the AERODYNAMICS area is delivering the external shape, and afterwards the STRUCTURES area is delivering an optimum structure for the fixed aerodynamic shape.

A lot of effort is invested in the aerospace community to transform this historical sequential process in a concurrent multidisciplinary process:

- ref. 4. shows the application of advanced CFD-codes combined with FE-modelling to the multidisciplinary optimisation of a commercial aircraft wing.
- ref. 5 shows an integrated aerodynamic-structural-control wing design for a forward swept wing. It follows the General Sensitivity Equation (GSE) method developed by Sobieski (ref. 6).
- also in Europe activities are developed in this field . In 1996 and 1997 a BRITE/EURAM MDO-project programme will be executed in which most of the european aerospace industry is participating (ref. 7). Objective of this project is to establish and demonstrate methodologies for simultaneous aerodynamic, structural and control system optimisation.

7.2. Systems Engineering and MDO

Systems Engineering builds from a top-down view on the system to be developed. Systems Engineering is the discipline of translating requirements into a specification of components which, when combined together, will satisfy the requirements. This is done in several steps. First, requirements are translated into an integrated functional description of the black box behaviour of the system (system analysis). Next, these functions are decomposed and allocated to components in a system architecture (architectural / conceptual design). Usually several alternative concepts are defined and evaluated against defined trade-off values. Systems Engineering has a lot in common with an IAD process. The first integrated tools are starting to appear to support the Systems Engineering process (ref. 8). A need exists to connect the modelling used in Systems Engineering with tools for specific engineering disciplines. As was stated in ref. 8: *"Ultimately, the systems engineering support tools must be fully integrated into frameworks containing tools supporting the other disciplines ..."*

MDO builds from bottom-up, applying integration concepts to the analysis models of the various disciplines. Sobieski (ref. 6) describes a systems approach to MDO. This approach builds on the method of decomposing the total system in subfunction / subsystems. Thus a very large optimisation problem is decomposed in much smaller ones many of which may be solved concurrently. Trade-offs to be made within each subproblem are guided by improving the object function of the total system.

The approach is visualised in fig. 17. The following steps are made:

- Start the design with a description of the system objective function, design variables and constraints.
- Analyse the system and define a functional description of the system (i.e. aerodynamics, structures, control, etc.). A formal description of functional dependencies based on N-square charts is used to support this process. For each function an analysis model (CAE-model) must be made available .
- Perform a system sensitivity analysis and form a Global Sensitivity Equation (GSE) which represents the systems internal couplings and sensitivities.
- Optimise the design variables with respect to the object function (trade-off).

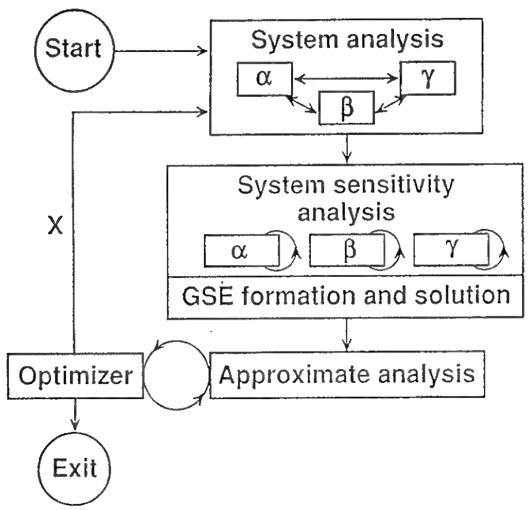


Fig. 17: flowchart of the System Optimisation Procedure (from ref. 6).

In principle this MDO-concept is capable of considering the entire aircraft as an engineering system, including aspects as maintainability, producibility etc. The challenge is to build an adequate functional description and to provide the analysis models + sensitivities.

The common problem addressed in developing Systems Engineering tools and MDO-tools is the control of interactions that occur among disciplines and physical subsystems in order to improve the entire system performance. A logical step would be to further combine the strengths of both these approaches.

7.3. Visualisation of the IAD process

We have visualised our IAD process vision on a poster. It can be used as an aid during discussions about opportunities for process improvement. In the years ahead a lot of effort and expertise from design engineers, process developers and IT-specialists will be needed to bring this poster alive. The benefit will be that the real strength of computer applications in engineering will become available in such an IAD process.

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A Concurrent Engineering Product — Airbus Aircraft Technology
(Développement et ingénierie simultanée — les produits airbus)

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CONCURRENT ENGINEERING IN AIRBUS
CONTEXT (1)

Evolution of company structure according to the economic environment

Decade	Economic Environment	Objective	Company structure
50	Post-war	Rebuild	Taylor-type model
60	Consumer society	Produce more	Proliferation of production facilities
70	Oil crisis	Produce quality, durable goods	Rationalization of investments made in the 1960s
80	Growth	Produce more efficiently	Integrated company branches
90	Recession Unsettled markets	Produce more rapidly	CONCURRENT ENGINEERING

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

CONCURRENT ENGINEERING IN AIRBUS
CONTEXT (2)

The context is changing

Today,

to be competitive on the world market, Airbus partners over Europe must

work

- **more together**
- **more simultaneously**
- **quicker**

on the same a/c zones

This requires common partner tools, with the creation of multiskilled, multi-partner groups to reduce cycles and costs

CONCURRENT ENGINEERING IN AIRBUS
CONTEXT (3)

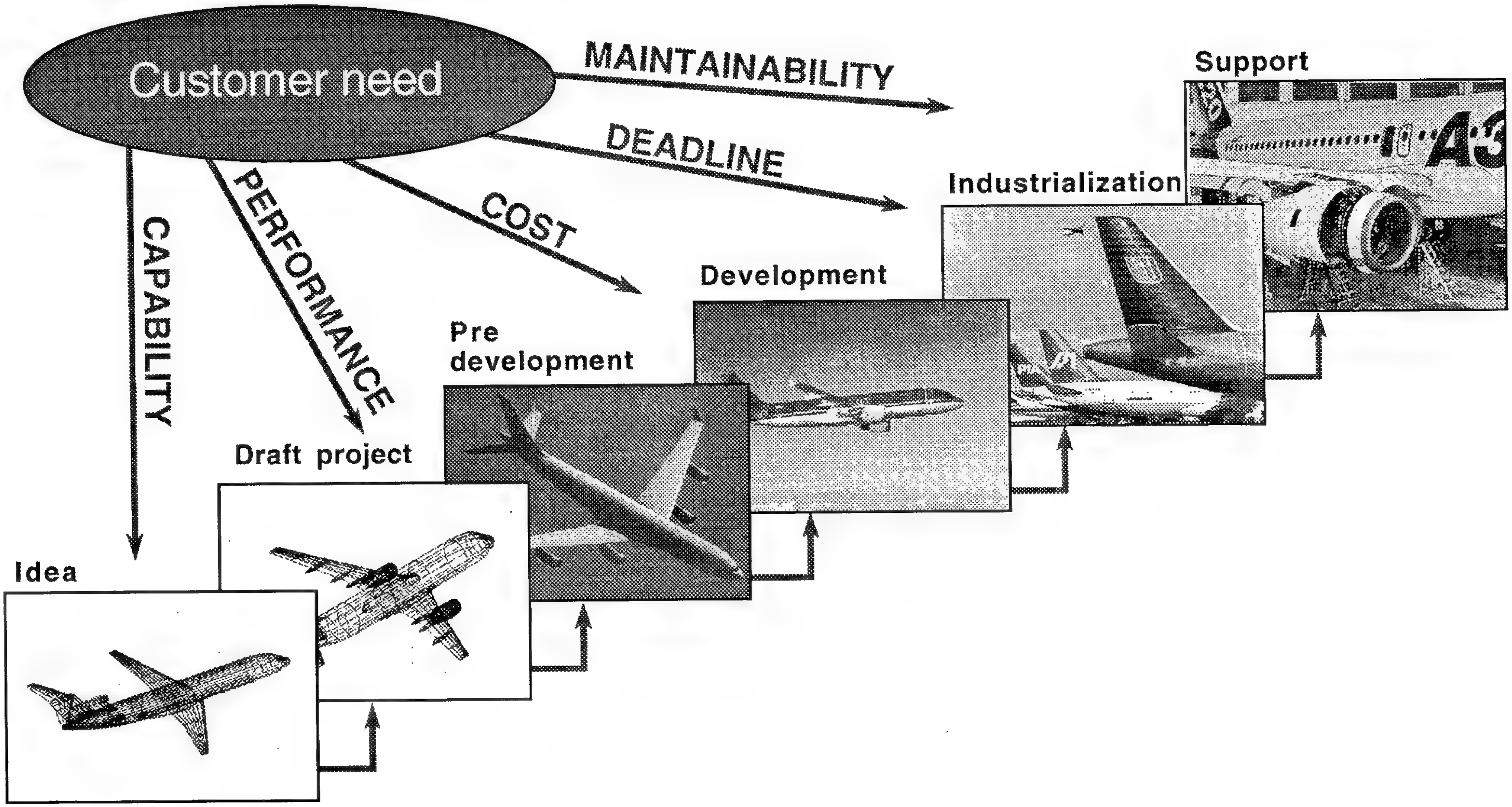
Before

- The manufacturer is also the designer

Now / Tomorrow

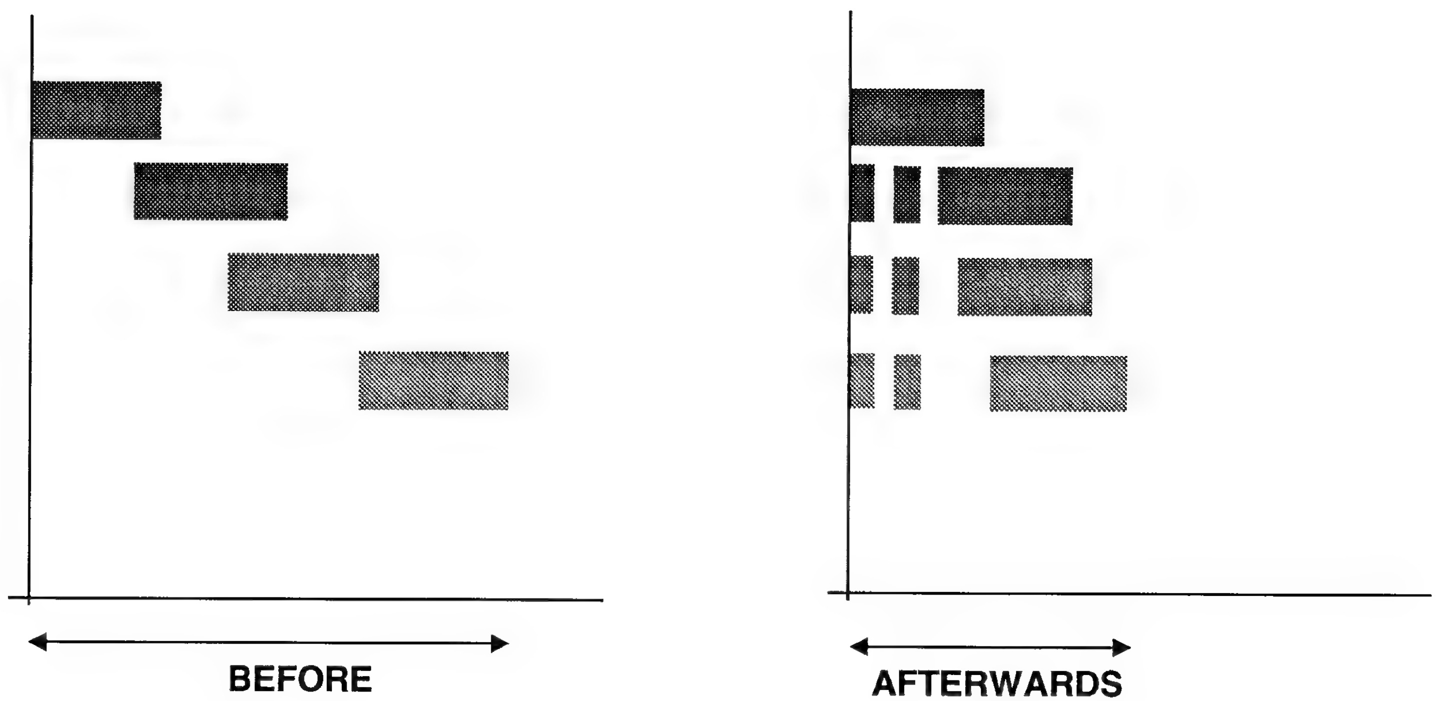
- The manufacturer is not necessarily the designer
- A partner designs elements and systems which may be in another partner's section
- Processes, methods and tools must therefore be adapted to this more complex system of work

CONCURRENT ENGINEERING IN AIRBUS
KEY POINT N°1 : GLOBAL DEVELOPMENT

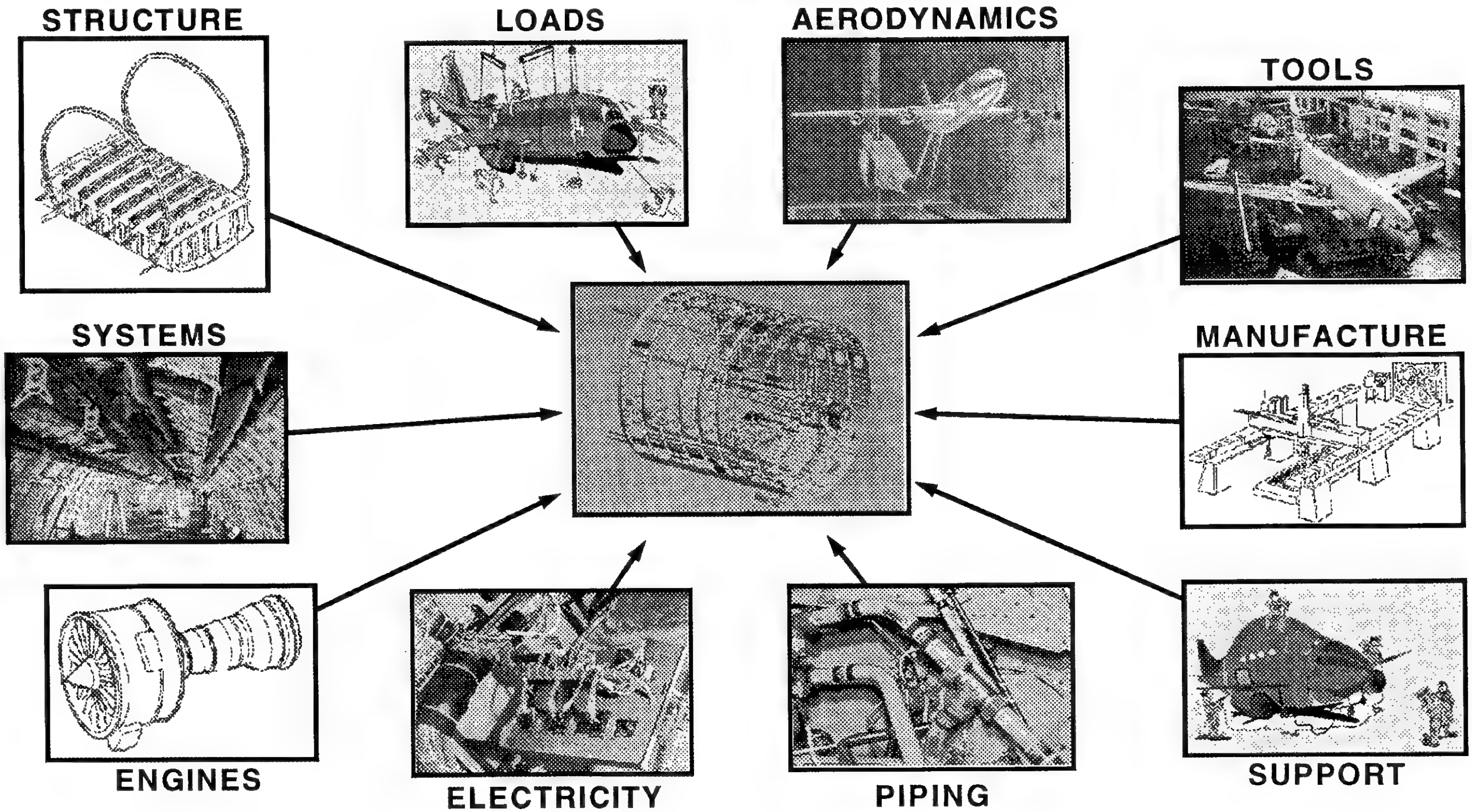


CONCURRENT ENGINEERING IN AIRBUS

KEY POINT N°2 : SIMULTANEOUSLY



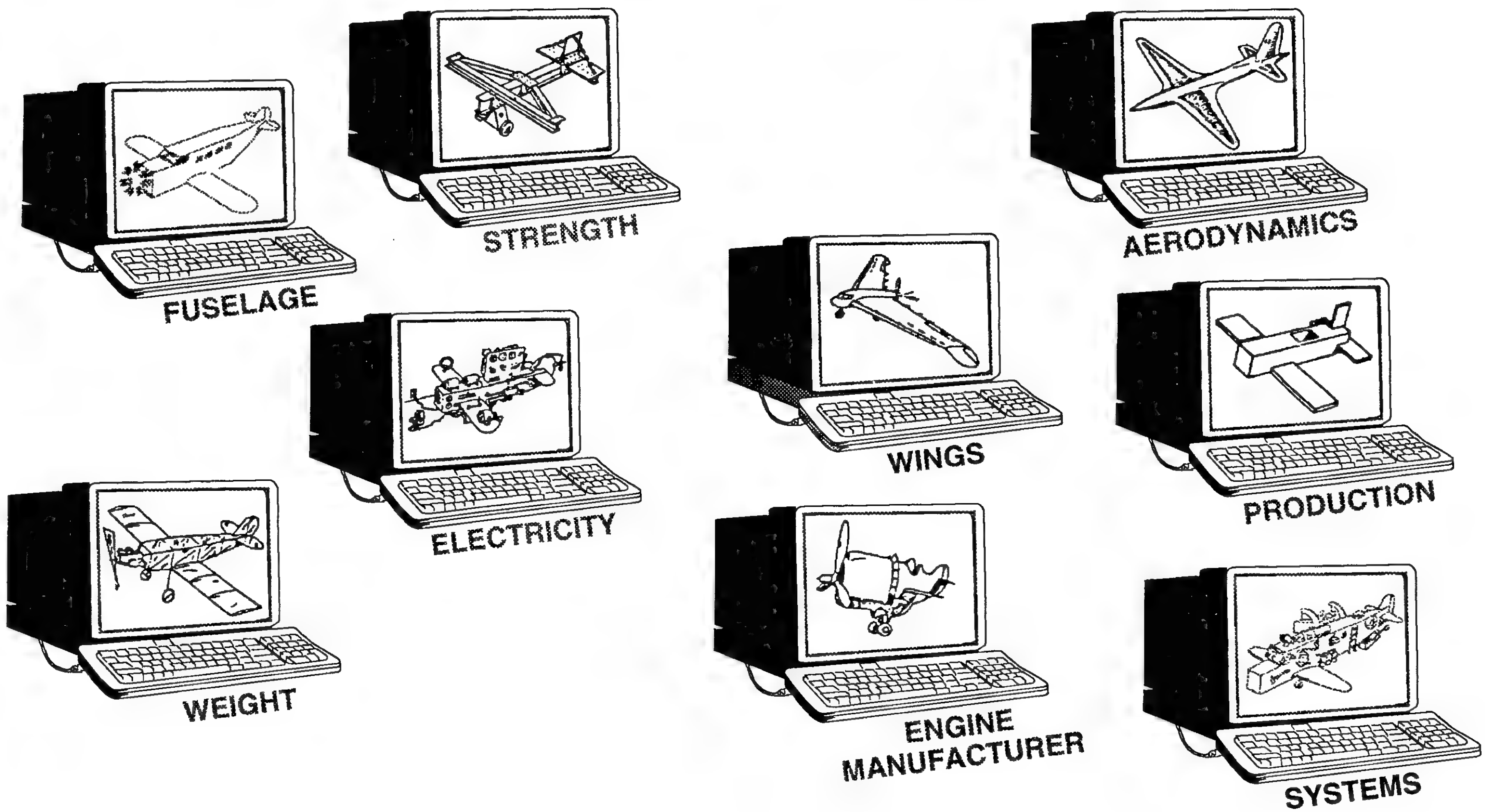
CONCURRENT ENGINEERING IN AIRBUS
KEY POINT N°3 : WE CAN ALL WORK TOGETHER



...the evolutions of which are **instantly** taken into account and made **accessible to all**

CONCURRENT ENGINEERING IN AIRBUS

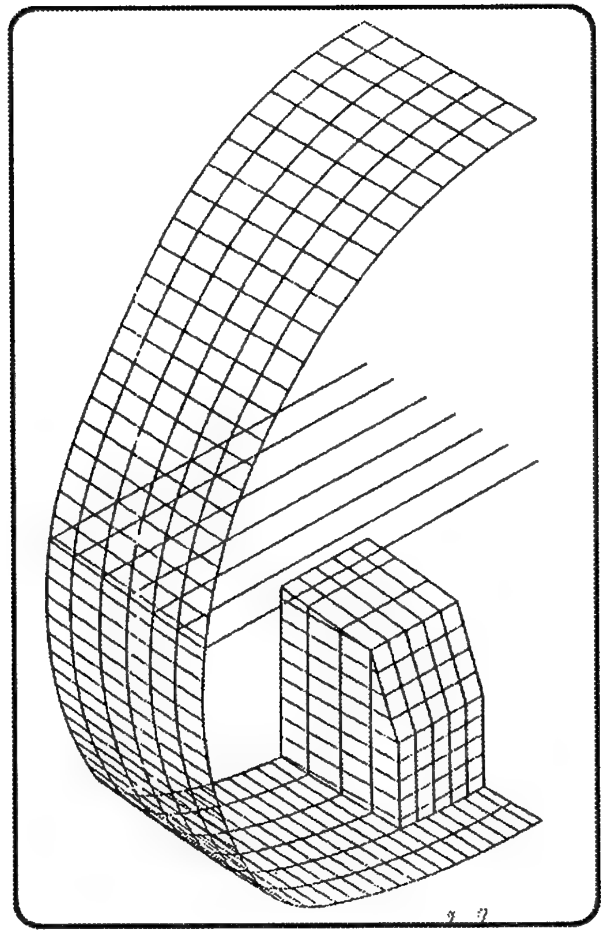
VIRTUAL AIRCRAFT WITHOUT CONCURRENT ENGINEERING



CONCURRENT ENGINEERING IN AIRBUS
EXAMPLES FOR ILLUSTRATION

Automatic drawing of finite elements

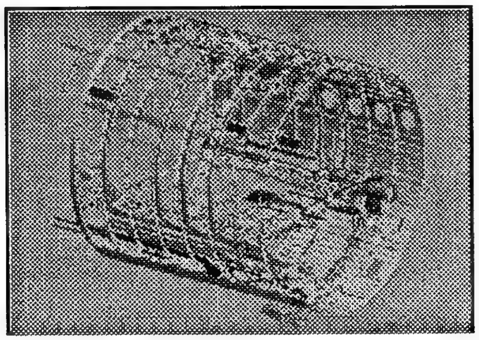
- ⇨ **Productivity gain of up to 75% (for the finite elements drawing task) + increased quality**
- ⇨ **Reduced cycle for the first calculation loop, which sets the process duration**



CONCURRENT ENGINEERING IN AIRBUS

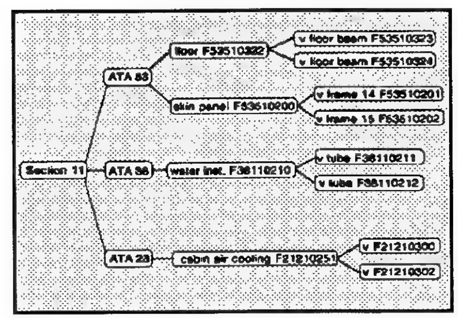
CONCURRENT ENGINEERING WITHIN THE AIRCRAFT BUSINESS IS POSSIBLE

Thanks to our "design build team" culture
(as early as 1978)

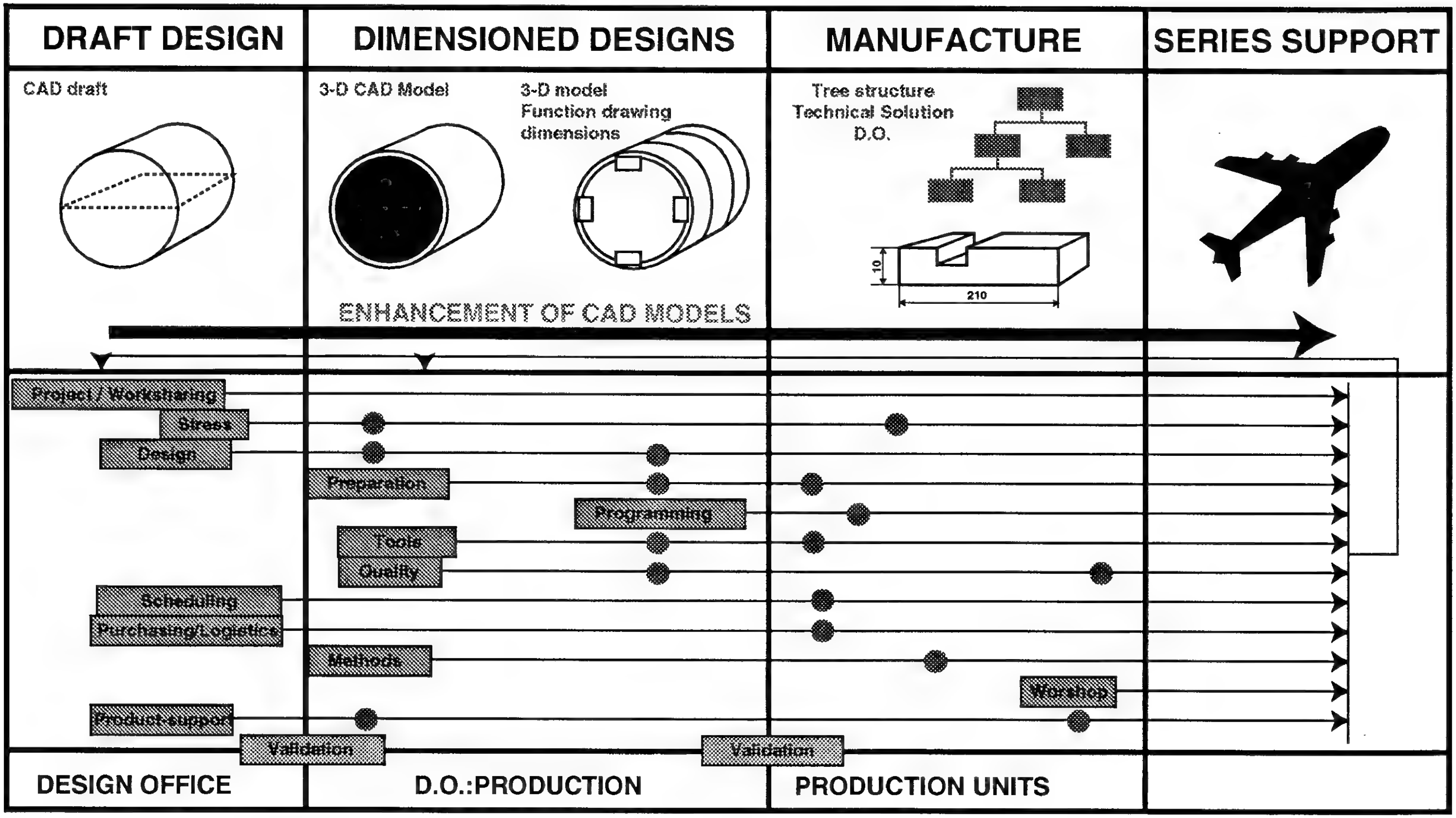


Thanks to virtual mock-ups

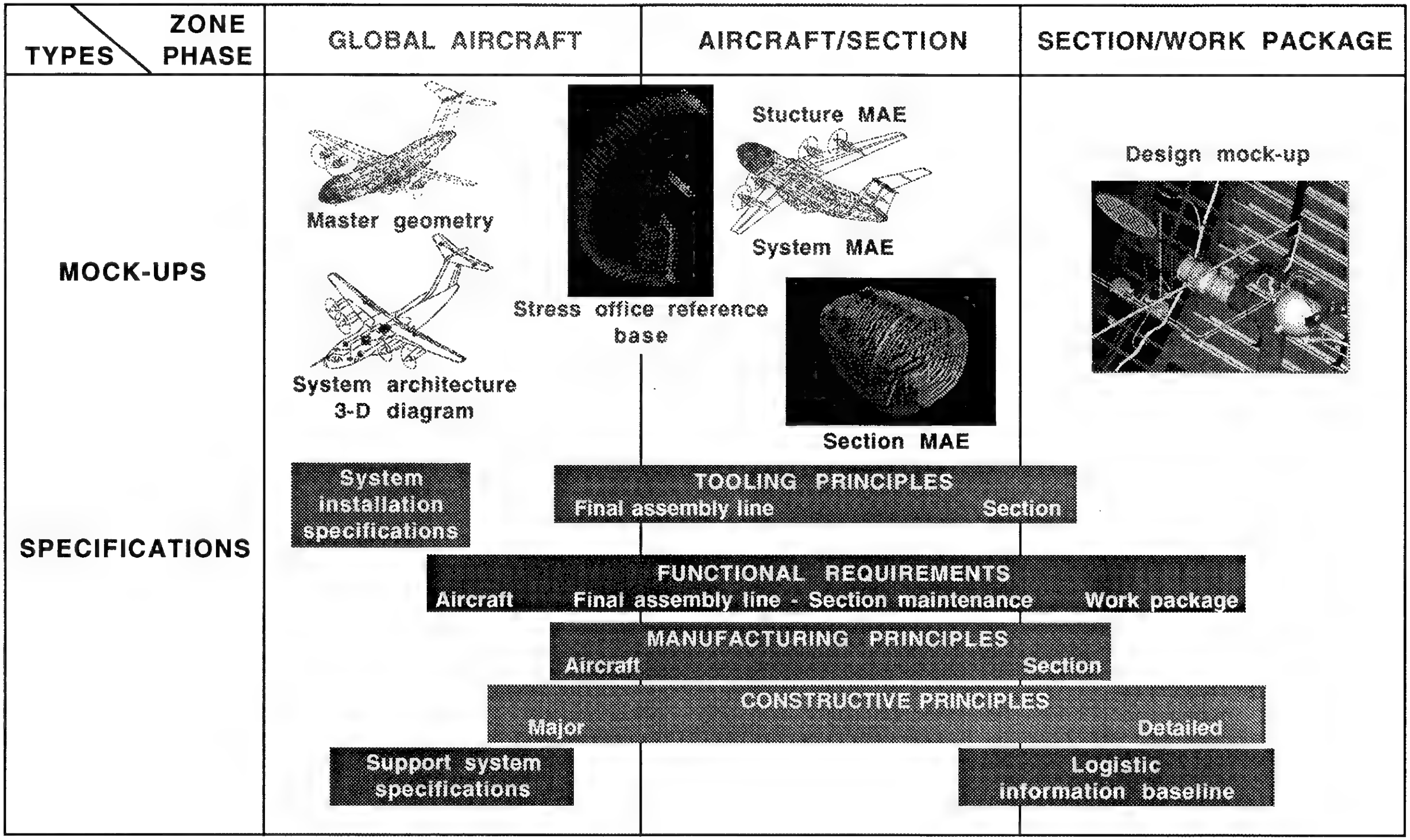
Thanks to unique databases shared by
all the actors



CONCURRENT ENGINEERING IN AIRBUS
MECHANICAL BRANCH



CONCURRENT ENGINEERING IN AIRBUS



Conception et Analyses des Cellules
(Design and Analyses of airframes)

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RESUME

On présente le processus d'**interactions dessin-analyses** dans la conception des cellules d'avion, permis par les capacités de nos outils couplés de CAO et de calcul CATIA et ELFINI :

- En avant-projet, définition globale de la cellule par **objets CATIA paramètrés**, associée à une **modélisation globale Eléments Finis** et d'une optimisation mathématique du dimensionnement ; les évaluations d'architectures alternatives peuvent être nombreuses, rapides et peu coûteuses,

- En phase de développement, dessin de détail des pièces par **modèles "solides"**, aménagement étudié avec une **maquette numérique**, vérification par **calcul Eléments Finis non linéaire** "local" et par essais partiels.

Compte tenu des limites des moyens numériques et des essais partiels, la démonstration de qualification doit aussi s'appuyer sur des **essais généraux** (essais en vol et cellule d'essais statique).

Les perspectives de développement des outils sont évoqués : **optimisation multidisciplinaire et multi-niveaux**, disponibilité **d"historiques" de conception** rejouables, **Feature Modeling** généralisé au calcul et à l'optimisation. Ces moyens donnerons encore plus de facilité d'itération à tous les stades de projet ; ils permettront de maîtriser pleinement les coûts, délais et risques dans les phases de développement. Ils posent cependant le problème de la préservation des capacités d'innovation avec la standardisation complète des dessins et des processus impliquée par ces nouveaux outils.

ABSTRACT

We present the process of drawing-analysis interactions for airframes design, corresponding with the capabilities of our coupled CAD analysis tools CATIA and ELFINI :

- For preliminary project, global definition of airframe by **CATIA objects** associated with a **global Finite Element model** and with a **mathematical optimisation** of the dimensioning ; many, fast and cheap evaluations of alternate architectures are possible,

- For development phase, detail drawings of parts with CAD **"solid" models**, lay-out studies with a **digital mock-up**, verifications by **non linear Finite Element analyses** or by **partial tests** ; the present heaviness of the process restricts design iterations.

Due to limitations of numerical means and of partial tests, the demonstration of structure qualification must be jointly founded on general tests (flight tests, static test airframe).

Prospects of tool development are evoked : **multidisciplinary and multilevel optimisations**, availability of replayable **Design Historical Records**, **Feature Modeling** generalised to analyses and to optimisation. These tools will give still more facilities for iterations at every project stage, they allows to fully master costs, time and risks in project development phases ; yet they pose the problem of preservation of **innovation** capability with the implicated full standardisation of designs and processes.

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

1 - INTRODUCTION

Le processus de conception est une suite d'interactions entre, d'une part l'imagination et la définition d'un produit, et d'autre part son dimensionnement et la vérification des performances attendues.

Pendant toutes les phases d'un projet, l'organisation de ces itérations définition - analyses doit être adaptée en fonction des capacités et des limites des moyens disponibles, en particulier :

- les outils de C.A.O. supportant la définition,

- les outils de calcul numérique et d'optimisation mathématique,

- les moyens d'essais,

- les techniques de calibration de modèles numériques sur les résultats expérimentaux,

les facilités de connexions entre ces moyens jouent aussi un rôle essentiel.

Nous illustrons ce sujet en présentant l'organisation qu'on préconise pour le développement des cellules d'avions militaires ; on fait ressortir les liens entre cette organisation et les capacités de nos outils couplés de CAO et de calcul CATIA et ELFINI.

Nous présentons ensuite certaines évolutions attendues de ces outils et des processus de conception correspondants.

2 - PHASE AVANT-PROJET

L'idée directrice est qu'il est possible de supporter les études avant-projet, par des évaluations de performances structurales beaucoup plus précises que par le passé. Dès ce stade, on peut maintenant utiliser intensivement, pour l'évaluation de grands nombres de dessins alternatifs, les méthodes d'analyse et d'optimisation qu'on réservait autrefois pour la phase de développement.

Les grandes lignes du processus sont les suivantes :

- A partir de la donnée d'un nombre restreint de paramètres globaux de définition "avion", on génère, une définition géométrique globale de la cellule : dessin général de structure et aménagement des grands équipements (voir planche 1). Cette définition prend la forme d'**objets CATIA**, portant dans leurs attributs les principes de technologies structurales retenues (exemple : matériaux, types de raidissage, ...),

- Les diverses analyses structurales et l'optimisation du dimensionnement sont menés par ELFINI, en prenant comme entrée le modèle CATIA précédent de la cellule globale.

  Le tronc commun de ces analyses est un **modèle global Eléments Finis** de l'avion complet (voir planche 1), à partir duquel sont effectués :

  - Les calculs d'**aéro-élasticité** et de **Flutter** (voir références 1, 2),

  - Les calculs de **charges en vol** et **au sol** (voir références 2, 3, 4),

  - Les calculs de répartition d'efforts internes, de contraintes moyennes et de critères de résistance correspondants.

  L'**optimiseur mathématique** d'ELFINI couvre l'ensemble de ces analyses. Il donne directement le dimensionnement moyen des peaux et des raidisseurs correspondant à une masse minimale, en satisfaisant un jeu de contraintes d'optimisation constitué de critères de résistance structurale, de marges de Flutter, d'aéro-élasticité statique et de qualité de vol, etc... (voir références 5 et 6).

L'utilisation intensive de ces outils est peu coûteuse, les temps de réponse sont rapides, grâce aux caractéristiques suivantes :

- Le lien direct entre le modeleur géométrique de CATIA et le générateur de maillage d'ELFINI,

- Les données de dimensionnement qui sont générées automatiquement par l'optimiseur et ne sont donc plus à fournir par l'opérateur,

- La disponibilité avec le système ELFINI, d'"**Historiques**" des données du processus : maillage, chaîne des calculs, optimisation ; ce qui permet :

  - de rejouer le processus pour les itérations de projet en n'ayant à fournir que les seules données modifiées,

- la préparation à l'avance de "**modèles standards**" de composants structuraux (modèle CATIA + modèle d'analyses/optimisation ELFINI), le **mailleur "topologique"** de CATIA-ELFINI permettant de s'adapter automatiquement a une forme géométrique paramètrée,

- La création d'une base de donnée, fournissant pour chaque type de composant structural les termes de correction entre les masses issues du modèle Eléments Finis et les masses réelles,

- Les performances intrinsèques des algorithmes d'ELFINI, renforcées par la puissance des ordinateurs actuels.

Avec ces outils les délais de réponse de l'analyse / optimisation structurale dans les itérations d'avant-projets sont typiquement:

- De quelques heures pour traiter de changements de spécifications sur une architecture déjà modélisée,

- De quelques jours si le modèle d'architecture peut s'obtenir par combinaisons et "isomorphismes" de modèles "standards",

- De quelques semaines si l'architecture est complètement nouvelle.

Un autre avantage notable de cette approche est l'objectivité des comparaisons entre solutions alternatives, garantie par l'optimisation mathématique ; la subjectivité est reportée en amont sur le choix des critères.

Avec ces outils et ce processus, si on ne fait appel qu'à des technologies structurales déjà validées, on aboutit, en fin de phase avant-projet, à une véritable conception implicite de la cellule avec une estimation précise de ses performances ; les risques de difficultés apparaissant dans les phases ultérieures de développement sont faibles.

3 - PHASE DE DEVELOPPEMENT

Pour la définition détaillée de la cellule (liasse), les relations dessin-analyses suivent globalement le schéma présenté planche 3, soit :

- Le perfectionnement du modèle général Eléments Finis et des modèles d'analyses attachés (aéro-élasticité, charges, flutter), en raffinant progressivement le modèle général avant-projet (voir planche 2), ainsi que la modélisation des charges aérodynamiques (calculs C.F.D., soufflerie) et du système de commande de vol,

- Le dessin de détail est réalisé directement avec des modèles C.A.O. tridimensionnels "solides", l'aménagement est vérifiée par une **"maquette numérique"** (voir planche 4). Le prédimensionnement des pièces est effectué de façon "classique" à partir des flux d'effort locaux et des consignes de dimensionnement "moyens" issus de l'optimisation mathématique sur le modèle général E.F.

- La validation des dessins de détail est supportée par des modèles Eléments Finis locaux, le plus souvent non linéaires (postflambage, plasticité, contact, ..., voir planche 5), couplés au modèle E.F général. La prévision des déformations et contraintes locales est relativement précise (voir planches 6), le point faible est celui d'avoir une connaissance des contraintes admissibles cohérente avec le niveau de détail des analyses ; il en résulte la nécessité de mener des essais partiels pour les zones sensibles où on ne fait pas appel à un dessin standard.

La relative lourdeur des analyses de détail (calculs et à fortiori essais) font qu'elles sont menées parcimonieusement, d'où risque d'impasse ; il est difficile d'itérer avec le dessin. Ces analyses de détail contribuent souvent plus à la vérification finale des dessins (dossier de justification) qu'à une "optimisation" des pièces.

4 - ESSAIS GENERAUX

La nécessité des essais généraux de qualification résulte des limites des moyens numériques actuels résumées sur le tableau 1. On considère, qu'avec ces moyens numériques, on restreint de façon acceptable les risques d'erreur majeure de conception ; mais à eux seul les calculs sont insuffisants pour assurer la qualification de la structure au degré de sécurité requis. La démonstration de qualification doit donc être basée conjointement sur les essais généraux et sur les calculs.

Tableau 1

Type d'analyse	Limites
Aéro-élasticité statique et charge	- Précision des calculs **d'aérodynamique transsonique**
Flutter	- Aérodynamique instationnaire **transsonique** - "Flou" des modèles dynamiques
Choc et vibration moyenne fréquence	- Modèles dynamiques - Modèles aéro-acoustique
Modèles généraux Eléments Finis	- **Erreurs humaines** dans les manipulations de données et de résultats
Modèles locaux E.F. et analyses structurales locales	- Erreurs humaines - Impasses - Connaissance des **contraintes** admissibles

Les essais généraux structuraux sont de 2 types :

- **Essais au sol et en vol sur les avions de développement**
  Outre la mise au point globale de tout le "système", pour la structure ces essais participent surtout à la validation et au recalage des modèles généraux (voir tableau 2 et référence 7).

Tableau 2

Principaux types d'essais	Modèles recalés ou validés
Etalonnage statique de l'avion au sol (Réponse des jauges de contraintes sous différents chargements forfaitaires)	- Modèle E.F. général - Opérateurs de suivi des efforts internes pour les charges de vol (*)
Essais de vibration au sol	- Modèle dynamique
- Manoeuvre en vol (quasi statique) - Mesures • paramètres de vol • réponses des jauges de contrainte	- Modèle de charges aérodynamiques - Modèle aéro-élastique - Opérateurs de suivi des charges (*)
- Vibration en vol - Mesures • paramètres de vol • réponses accélérométriques	- Modèle aéro-élastique dynamique (Flutter) - Fonction de transfert aérostructurale (*)
(*) Pour la mise au point du Système de Contrôle de Vol	

Les modèles numériques validés et recalés sont utilisés à la fois :

- Pour évaluer les marges de sécurité dans l'ensemble du domaine de vol, vis à vis des phénomènes d'aéro-élasticité statique, de flutter et de couplage au Système de Contrôle du Vol,

- Pour valider et recaler les cas de charge dimensionnants appliqués sur la cellule d'essais statique.

- **Cellule d'essais statiques**
  Elle supporte la qualification de la structure pour la résistance mécanique (en statique et en fatigue). La nécessité de ces essais statiques généraux, coûteux et contraignants, résulte de ce qu'on ne peut garantir qu'aucun défaut de dessin ne passe le filtre des calculs sur plan et des essais partiels (voir arguments tableau 1). Le recalage progressif des modèles au cours du déroulement des essais réduit le risque de rupture prématurée de la cellule d'essais.

5 - PERSPECTIVES

La tendance est de perfectionner considérablement, les outils et leur processus d'utilisation pour faciliter les itérations dessin-analyses/optimisation à toutes les étapes du projet ; citons parmi les développements les plus attendus :

– Les techniques d'optimisation multidisciplinaire et multi-niveau

Elles viennent dans la suite de l'utilisation en avant-projet de modélisations numériques fiables dans toutes les disciplines ; pour développer ces techniques on trouve comme problèmes :

- **L'identification des "modèles produits"** (ou modèles de définition) et des variables de conçeption associées, pertinents pour chaque niveau successif de définition ; les relations entre ces modèles "produits" et les modèles de calcul de chaque discipline ; les relations entre les modèles de définition et d'analyse des différents niveaux,

- Le développement des **outils de CAO "généralisée"** pour créer, manipuler et relier ces différents modèles numériques, celui du système de **gestion de données** correspondant,

- Les difficultés propre à **l'optimisation mathématique** dans ce contexte, par exemple :
  * le développement **d'analyses de sensibilité** dans toutes les disciplines concernées,
  * la manipulation simultanée de **variables de conception continues et discrètes,** l'état des variables discrètes définissant les modèles applicables ; ce qui conduit à hybrider des techniques classiques d'optimisation mathématique "continue" avec des méthodes d'Intelligence Artificielle,
  * le traitement des problèmes d'**extremums multiples** (conséquence du problème précédent),
  * les relations entre les optimisations sur les modèles de différents niveaux,
  * etc...

Ces développements se font progressivement en reliant successivement les optimisations existant à chaque niveau et dans chaque discipline ; un exemple est l'opération **"M.D.O."** menée par les avionneurs européens (contrat Brite-Euram), qui couple l'optimisation de la forme aérodynamique et du dimensionnement structural,

– Historiques de conception

L'idée est de préserver à la première itération de conception le jeu complet des données "sources" (entrées par l'opérateur) de la chaîne des modèles de définition/analyses/ optimisation, pour pouvoir le rejouer dans les itérations ultérieures en n'introduisant que les seules données modifiées. Cette idée est la généralisation de la notion d'historique existant dans ELFINI.

Outre l'intérêt de pouvoir récupérer des données de chaîne de modèle standard préparées à l'avance, la disponibilité d'historiques de conception est une condition pratique de l'"**Ingénierie Simultanée**". Les spécialistes de chaque discipline peuvent développer leurs modèles en parallèle, avec des spécifications provisoires, en sachant que le coût de la mise à jour ultérieure sera faible.

Jusqu'à présent, la difficulté de disposer d'historiques pour la définition était liée au caractère interactif des opérations avec la 1ère génération d'outil CAO. Les historiques de conception seront disponibles naturellement avec la modélisation par "feature" de la 2ème génération d'outil.

– Le Feature Modeling

C'est une nouvelle révolution dans l'art du dessin industriel, en réaction contre le privilège des seuls données géométriques avec les outils de CAO de 1ère génération.

Le Feature Modeling correspond à une définition sémantique du produit décrivant implicitement toutes ses caractéristiques (voir planche 7 et référence 8). Au delà du contenu d'un dessin classique, le Feature Modeling est aussi proposé pour la définition des processus et des outillages de fabrication.

Le codage informatique de la définition par Feature Modeling permet de vérifier automatiquement des "règles" de dessin ou de fabrication par des techniques de Système Expert.

Le Feature Modeling commence à être utilisé par Dassault Aviation pour la définition détaillée des pièces (tôlerie, pièce usinée, ...).

L'extension du Feature Modeling est étudié pour la définition d'ensemble de pièces avec leurs liaisons, allant jusqu'à celle de tronçons complets (projets Européens FEAST et CEDIX).

On espère, avec la généralisation du Feature Modeling, une diminution considérable des délais de définition, il devient alors crucial de ne pas oblitérer ce gain avec un processus trop lent de vérification par calcul.

La solution est **d'étendre les principes du Feature Modeling au processus de calcul et d'optimisation**. L'idée directrice est que les points sensibles structuraux à vérifier peuvent être aisément associés aux "Features" de dessin ; à partir de là il est possible de lancer automatiquement la chaîne de vérification par calcul (maillage, calcul EF, analyses locales, ..., édition des dossiers de justification) ; ceci pouvant s'étendre au dimensionnement automatique par optimisation structurale.

6 - CONCLUSIONS ET REMARQUES

L'émergence de la 2ème génération d'outil de conception basée sur le **"Feature Modeling Généralisé"** (dessin/calcul/optimisation) aura des conséquences sur l'organisation des projets:

- Par la plus grande facilité d'itération et de modification, à tous les stades d'avancement des programmes,
- Par la maîtrise, considérablement accrue, des risques, des délais et des coûts de développement industriel, avec une meilleure qualité des produits conçus, liée à la standardisation des dessins, des procédures de calcul et des gammes de fabrication, impliquée par le Feature Modeling,
- Par le plus grand rôle des modèles numériques dans les échanges entre partenaires de projet, non seulement pour traiter les problèmes d'interface géométrique et d'aménagement, mais aussi pour garantir le fonctionnement couplés des sous-ensembles et des équipements dans le système avion. Le comportement mathématique des modèles numériques de ces sous-ensembles, leur variabilité autorisée et leur processus de vérification ou de calibration expérimentale deviendront de véritables spécifications, exemples :
  - Les modèles Eléments Finis de tronçon,
  - Les modèles dynamiques non linéaire de train d'atterrissage,
  - Les modèles dynamiques d'équipement, d'emport, ...,

La **préservation des capacités d'innovation** est un point délicat à résoudre dans l'organisation de conception avec les nouveaux outils, la tentation devenant grande de ne rester qu'à combiner des concepts "standards" trouvés dans les bibliothèques de "Feature".

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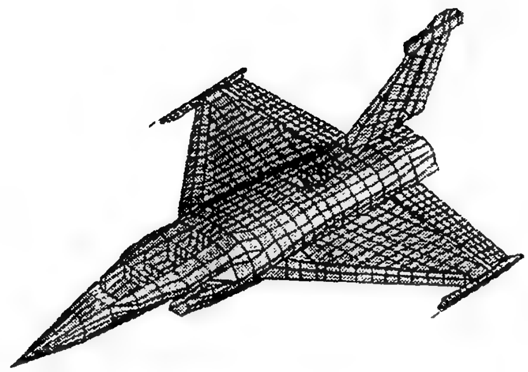
E.E.C. Directorate for Science Research and Development Join Research Center - BRITE EURAM Programme, 75, rue Montoyer Brussels - 1040 Belgium

PLANCHE 1
Modèles Avant-Projet

Modèle de définition



Modèle globale Eléments Finis

PLANCHE 2
Modèle Globale Eléments Finis
Phase de développement

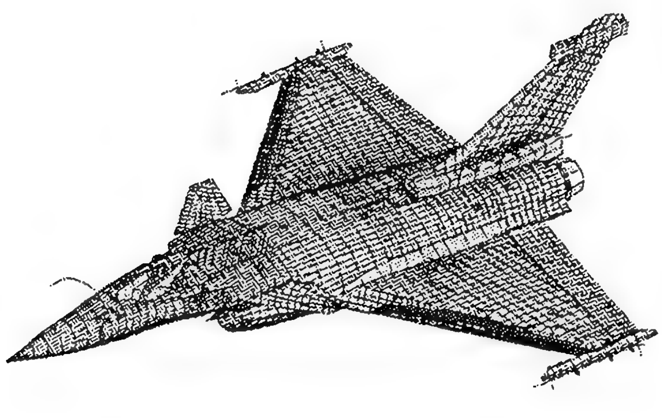


PLANCHE 3

RELATIONS DESSINS-ANALYSES EN PHASE DE DEVELOPPEMENT

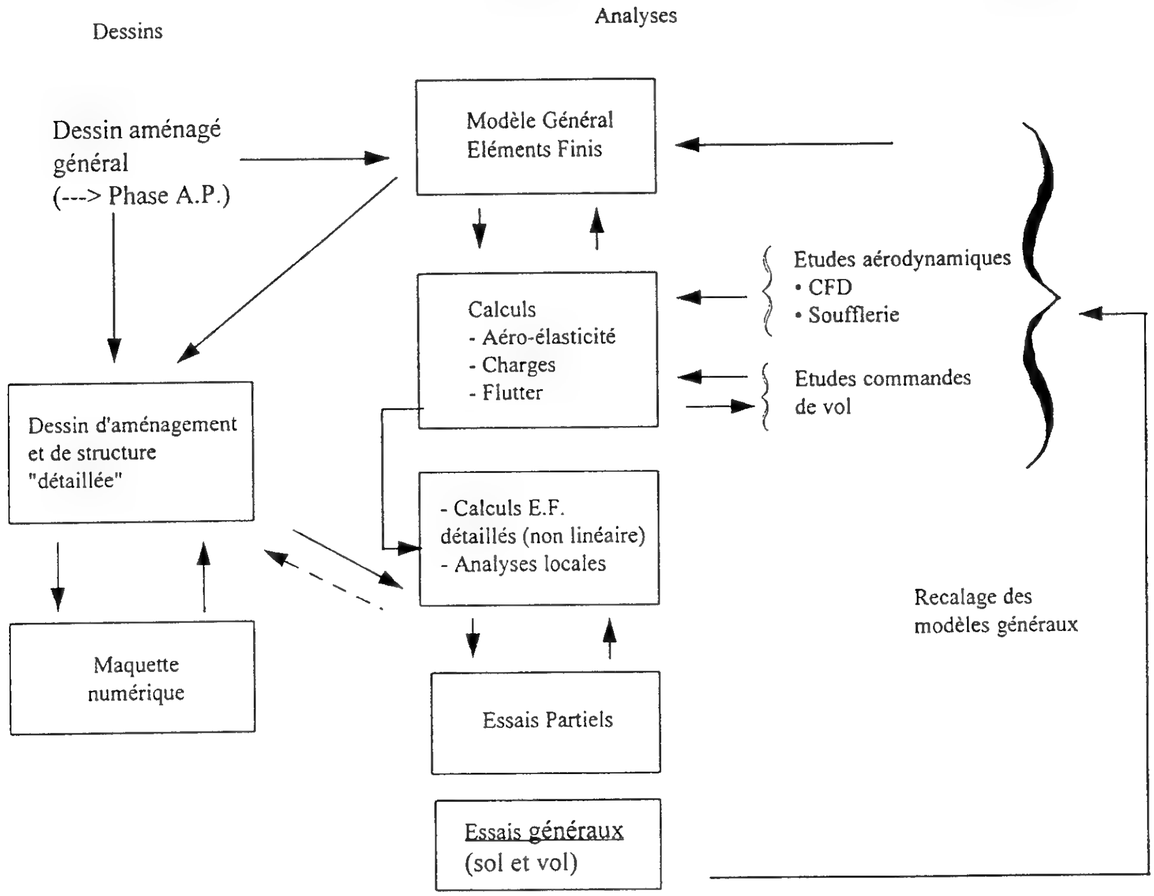
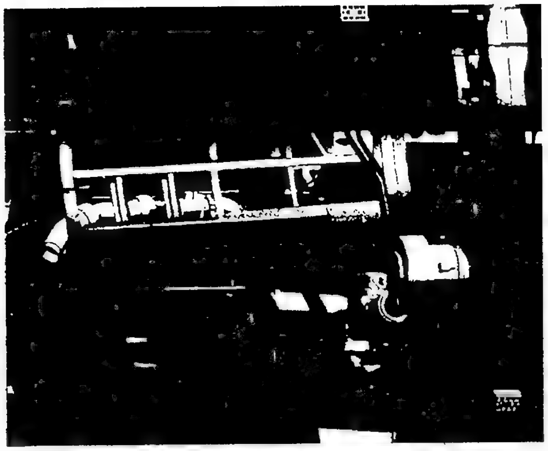


PLANCHE 4
Phase de développement
Modèle de définition « Maquette Numérique »



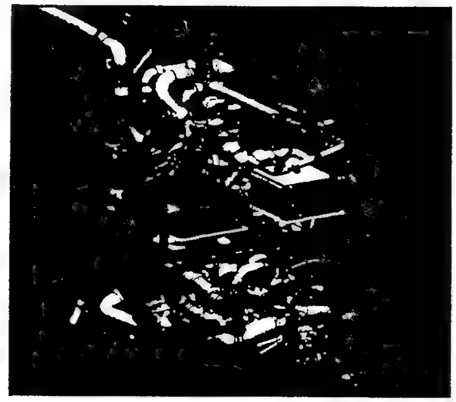


PLANCHE 5
Phase de développement
Calcul Elements Finis Locaux

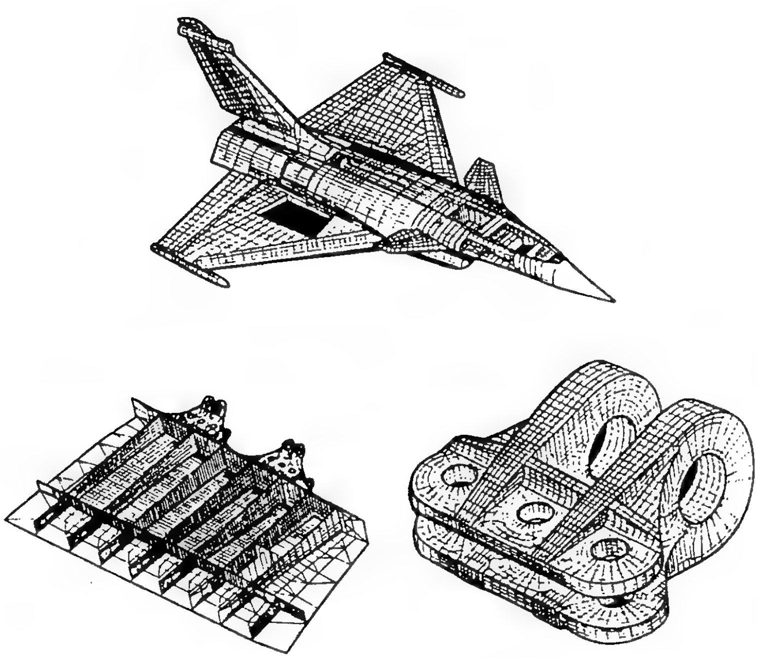
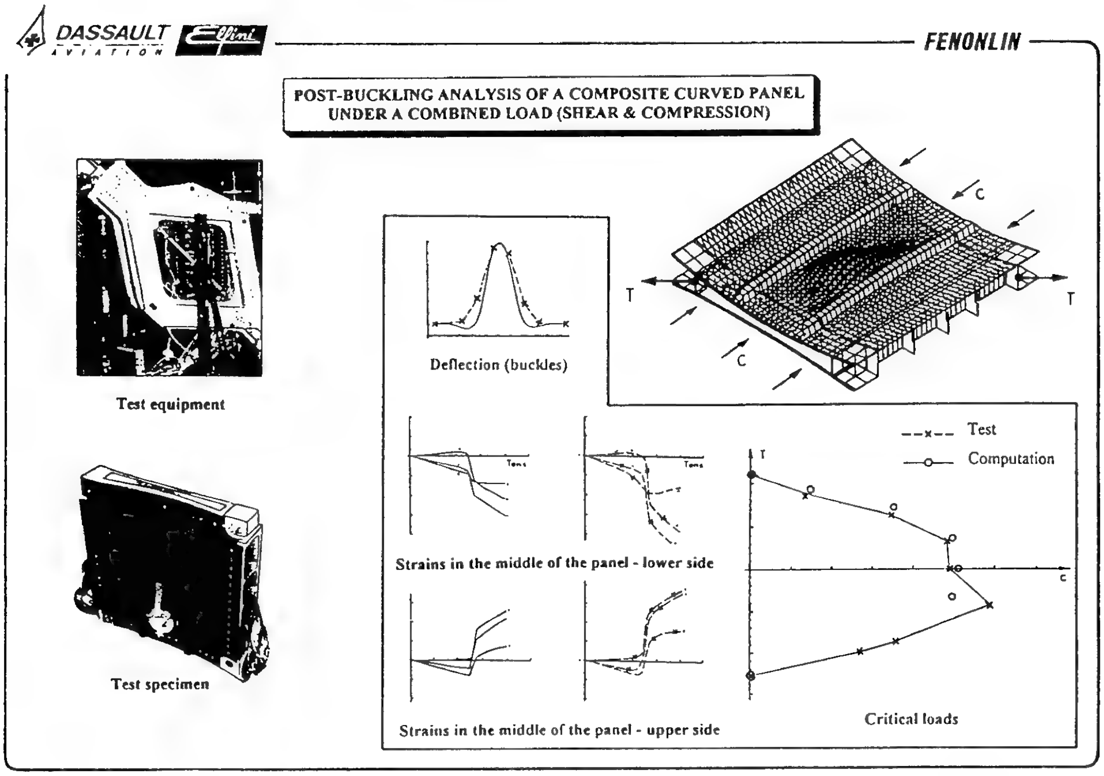


PLANCHE 6
Phase de développement
Calculs Elements Finis Non-Linéaires
Comparaison calcul-essais



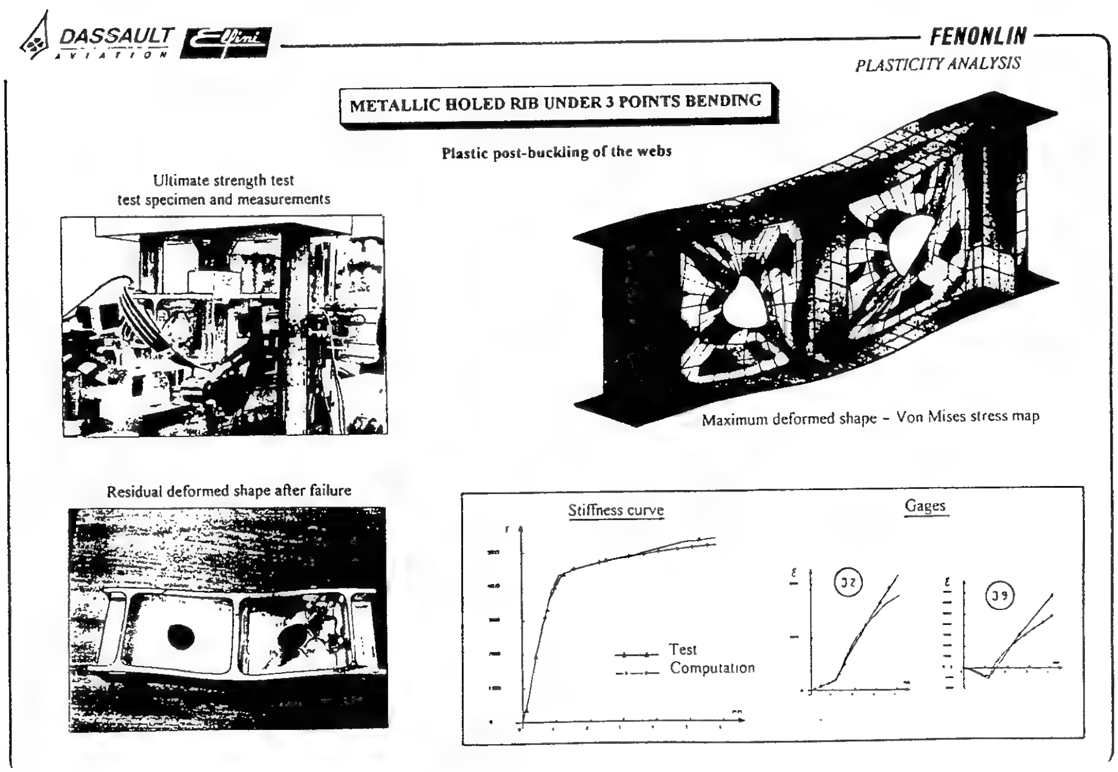
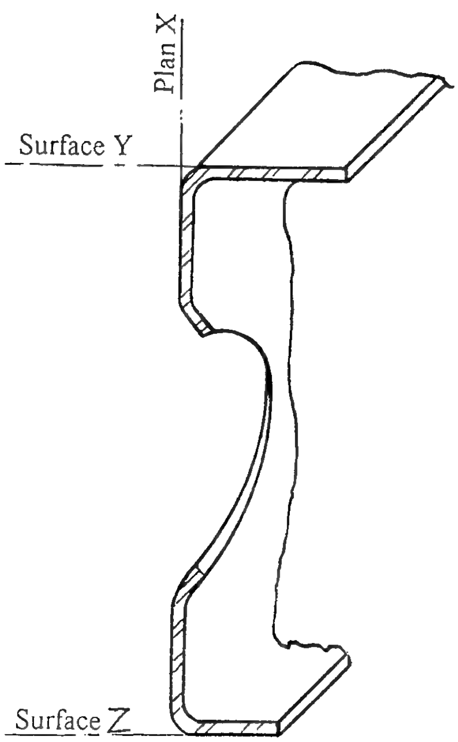


Planche 7

Principes (simplifiés) de la définition d'une pièce par « features »



Liste des « features »

- Type : Tôle cambrée,
  matériaux : 2024, Epaisseur : 1,2 mm
- Ame : Plan X*, sens +, ...
- Semelle : Surface Y*,
  hauteur : 40 mm, rayon de pliage : 5 mm,...
- Bord tombé 1 : Surface Z*,
  largeur : 35 mm, ...
- Trou, Ame, bord tombé,
  diamètre : 100 mm, distance : 70 mm,
  surface Y*,sens +, ...
- Etc ...

* Références géométriques définies préalablement

AUTOMATED STRUCTURAL ANALYSIS PROCESS AT ROCKWELL

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SUMMARY

An automated and integrated structural design and analysis process for aircraft and weapons airframes is described. The primary purpose of the process is to reduce design cycle time and tie structural design and performance to "design to cost" analyses. This capability is included in a general system, called the Affordable Systems Optimization Process (ASOP), which includes five separate, but linked systems: The "Design to Cost" Tool, Automated Structural Analysis Process (ASAP), an ultra rapid finite element model generator and transformation pre/post processor (COMETRAN), Active Aeroelastic Wing Optimizer (AAW), and CFD based static and dynamic aeroelasticity (ENSAERO). This evolving system has already significantly reduced structural design cycle time, and is being expanded to include more design disciplines.

1. INTRODUCTION

The increasing emphasis on affordability in aerospace vehicle design necessitates reduced design cost and design cycle time, with integration of the system cost estimates into the airframe structural design trade study process. Rockwell's approach to this "design to cost" philosophy is the development of an Affordable System Optimization Process, which includes five software systems that contribute to the structural design process.

The goals for these analysis systems are to:

1. Reduce the airframe design and analysis cycle time in all 3 phases of design (conceptual, preliminary and detailed design).
2. Increase structural design and analysis models fidelity earlier in the design process to achieve more accurate estimates of structural weight for conceptual design trades.
3. Expand the number of disciplines (manufacturing, supportability, cost, etc.) considered in the structural optimization process in an Integrated Process and Product Development (IPPD) environment.
4. Integrate conceptual and preliminary structural trades with "Design to Cost" analyses to define the designs with either "best value" (optimal balance of cost and performance) or minimum cost (with performance compromised).

2. DESIGN PROCESS - ACCURACY WITH HIGH CYCLE SPEED

Design is an "optimization" process employing large quantities of physics data from engineering disciplines to develop a manufacturable and supportable product meeting a customer's performance and life cycle cost (LCC) objectives. Optimization takes several forms depending upon the amount of uncertainty present in the design data and the sensitivity of the design to perturbations in the design variables. Examples of these design variables are the wing span, chord, thickness, camber and twist; structural material allowables, structural construction, landing gear length and type, control surfaces; surface deflection and deflection rate; power distribution, fuselage length and area distribution; and many other variables of design.

The design process is broken into several stages depending upon the maturity of the requirements and the completeness of the data sets. Typically for military weapon systems these are:

1. Conceptual Design: Seek a family of aircraft and weapons concepts satisfying both multi-mission performance and political-economic scenarios.
2. Preliminary Design: For an aircraft, seeks a configuration from a conceptual family that will meet all the known requirements with a specified level of risk (schedule, cost, performance, technology, reliability) at acceptable level of robustness to uncertainty.
3. Final Design: Seeks the physical definition of all structural, propulsion system, subsystem, avionics, and software which translates the robustness margins into useful productive features improving performance or reducing life cycle cost.

2.1 Conceptual Design To Accommodate Mission

Early in conceptual design, the requirements for completing the mission, satisfying performance, and political economic scenarios determine a configuration family for the aircraft and weapon and its supporting logistics structure. Often simulations and analyses are conducted in a cyclic fashion as shown in Figure 1. The goal is to develop a build-to-package of design information corresponding to the cost and performance data which meet

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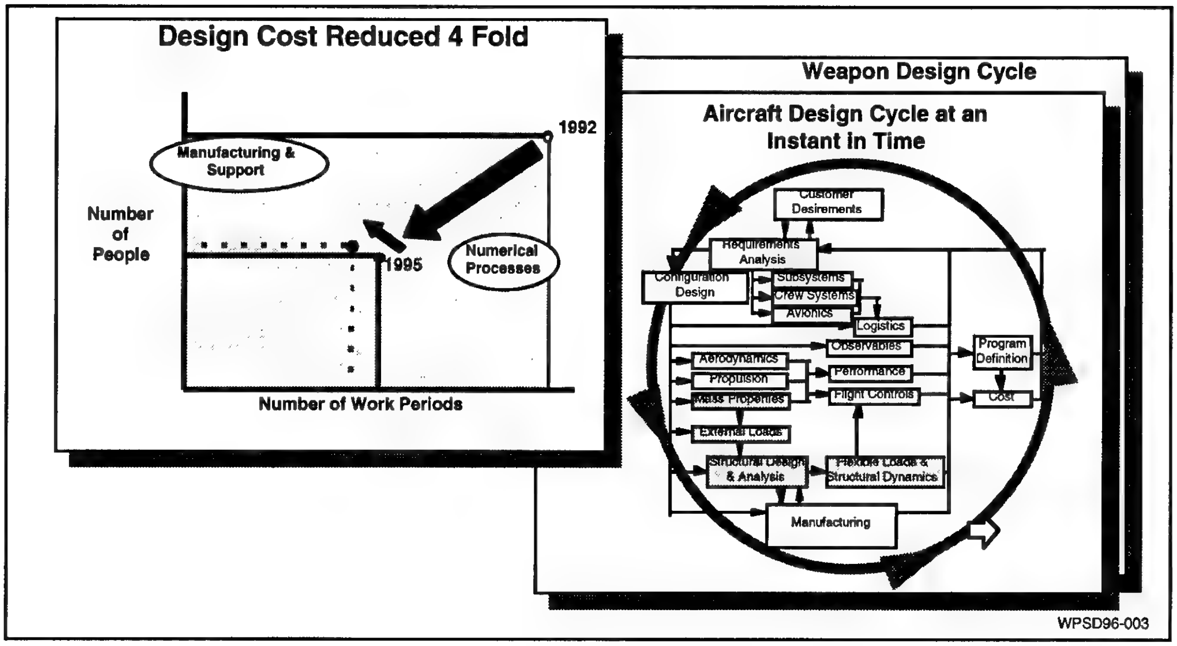


Figure 1. Conceptual Design Cycle Cost is Being Reduced.

the customer's requirements. Reducing cycle time by improving the numerical processes and process automation, can greatly reduce design cost.

Early requirements often stated as "desirements", or roughly stated user goals regarding payload, cost and range. As each cycle occurs, additional data from other disciplines are added. Examples are material definitions; structural concepts; topologies for electronics and subsystems; layouts determining volume for fuel and equipment; test, manufacturing, and logistics support plans; initial certification and qualification plans; and operational and system requirements documents. The logic shown relating the functional disciplines is representative of a step in time. Generally, given requirements a configuration drawing may be constructed. The configuration may be analyzed for aeromechanics, propulsion efficiency, weight, loads, observables, performance, controllability, and subsystem peak sizing loads. Under a Integrated Product and Process Development concept, engineering disciplines are joined with manufacturing, logistics and finance functions to ensure cost remains a design variable.

The process may begin with a cycle lasting only a few days and eventually become a cycle lasting a month or more. As the design progresses more and more of the life cycle cost are determined and "fixed" as important customer features for the design. An ability to provide easily visible relationships between cost and performance is of paramount importance, because all customers have a maximum they may spend, whose exceedence may cause a termination of the project if a "best value" design solution is not reached within that budget. Most probable cost estimates by the customer firmly institutional the best is not reached within that budget.

Key structural data available at the end of the conceptual design are:

1. Coarse FEM's with various candidate structural concepts and marerails
2. Limited set of "Critical" rigid external load-cases
3. Structural sizing based on strength and buckling
4. FEM Based Weights for major structure, statistical based weights for secondary structure

2.2 Preliminary Design to Define the Best of a Configuration Family

The initiation of preliminary design often is signaled by greater detail in configuration analyses, while studying more design variables, sensitivities and uncertainties. A successful conceptual design will offer challenges, but should not hold a major roadblock to further defining and narrowing of the design margins, while maintaining robustness. The margins must narrow to accommodate off-design point operation, evolving requirements, nonlinearities, new experimental results, and technology risk reduction.

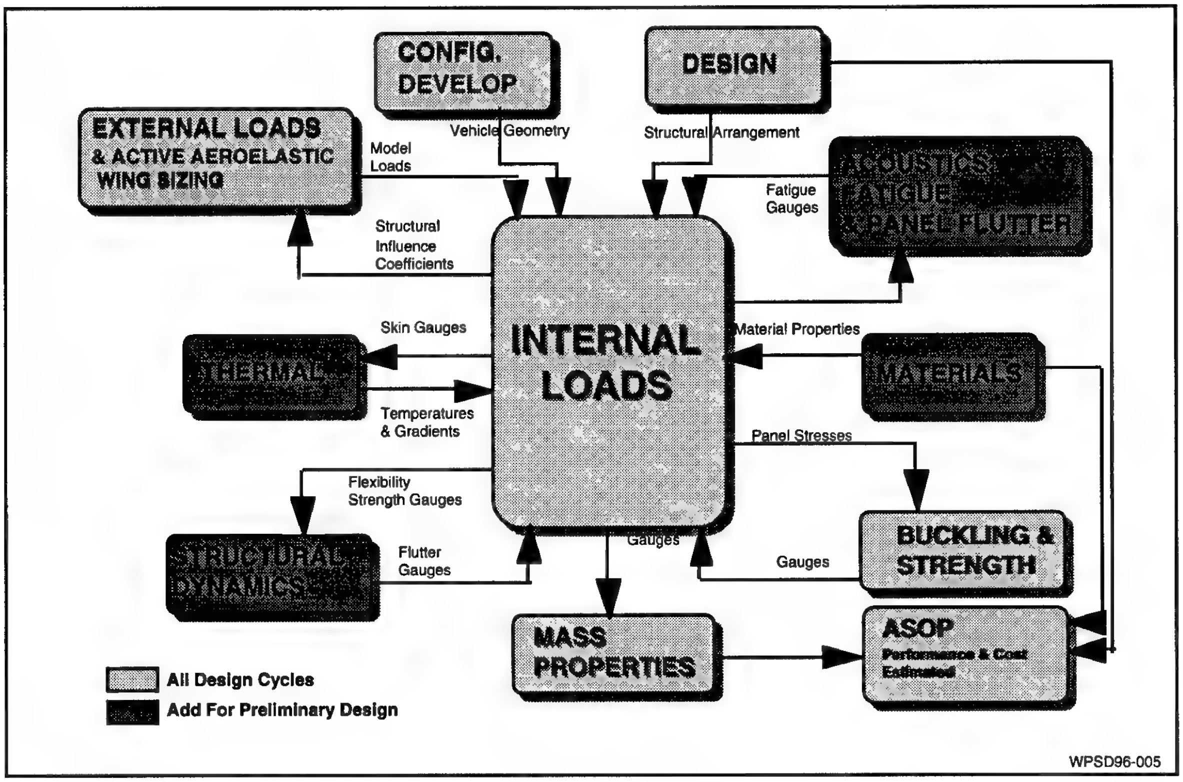


Figure 2. Preliminary Design Adds Design Disciplines and Fidelity

The greater detail of preliminary design may be portrayed by flow diagrams showing the major design summation points and the interfaces to other data sets. An example is found in Figure 2 for the "internal loads" computation comprising part of the "structural design & analysis" box show in Figure 1.

An inspection of the flow diagram shows that internal loads is interfaced to configuration development, design, acoustic fatigue and flutter, materials, buckling, mass properties, structural dynamics, and thermal loads. Active aeroelastic wing optimization may be included. Some of these interfaces are automated or semi-automated transfers of computer data. Others are manual interfaces requiring examination and discussion of the data among team members involved in the IPPD team. For this reason, cycle time compression is limited by the need for the manual activities associated with the formation of "design conclusions" (where data leads to a solution) and "executive decisions" (where an assumption must be made to continue the design process). All conclusions and decisions must be documented, with a goal of turning decisions into conclusions as additional design cycles occur.

Two problems may arise: (1) an unacceptable slowing of the design cycle and (2) an increase in the complex interaction of the design variables with life cycle cost. The first problem may be addressed by a thorough process diagram supported by historical process metrics collected for each design cycle. A typical example is presented in Figure 3, where the time to complete a Gantt chart milestone, on the critical design path at each design summation point, is plotted as a function of work periods. The chart shows a goal, a requirement and actual measurements collected for two cycles. Note in particular the steepening of the chart as the work by structures, controls and systems occurs. This indicates summations of large amounts of data for testing against the design requirements. Clearly, the structural design cycle is a major contribution to the system design cycle schedule.

The "goal" provides a future target for team efficiency; a "requirement" states the critical path the design team has accepted for the current cycle; a measurement indicates where monitoring of data occurs, signals a possible configuration design failure and forecasts the ease to which the design cycle may be accelerated. In this example the requirements are met everywhere except for a portion of the structural analysis, manufacturing, and logistics. Each is a candidate for staff and methods improvementto reduce design cycle time. In addition, these three areas and a portion of design did not meet the goal, signaling that a

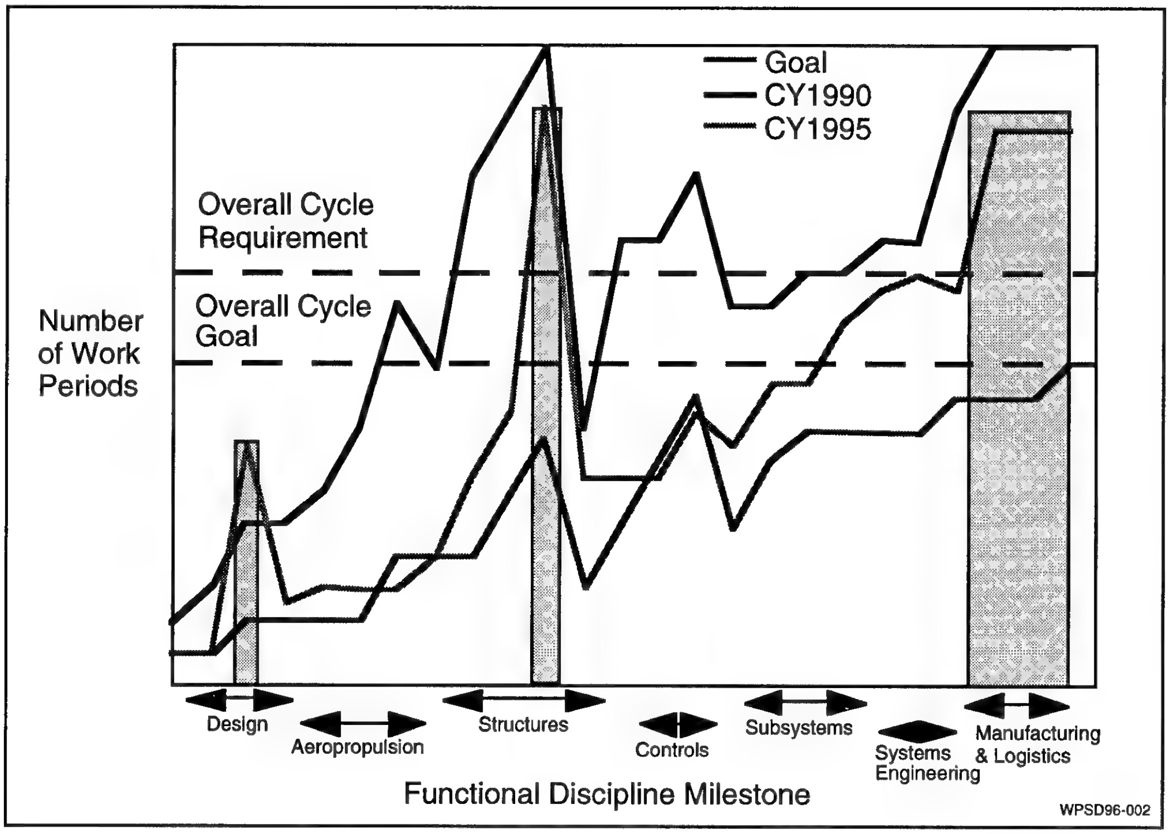


Figure 3 The Structural Analysis Process is a Major Contribution to the Design Cycle Time

design cycle acceleration may be prevented if the underlying problems are not addressed.

The second problem is the increased complexity of the interaction of cost with the design variables. This is to be expected since more knowledge and refinement of the dependent and independent design variables during preliminary design is a clear requirement. It is necessary to form a convincing design of the customer's product, before it may move to a final design stage. Dependent variables are those derived or computed from given or assumed independent variables. Independent design variables are those a design group is free to change to determine a product. The dependent variables are linked to the independent variables by processes, physics, geometry, and mathematics. An example is the area of a rectangular wing (dependent) defined by wing chord (independent) and wing span (independent). Another example is cost (dependent) defined by aircraft length (independent), material system (independent) and manufacturing method (independent).

The solution to this second problem is a design software tool set that captures the dependent-process-independent relationships, and then allows the arbitrary reversal of the dependent and independent variables for very high order systems. Rockwell's software to perform this function is characterized in Figure 4. The portrayal is for a design-to-cost application, in which the engineering, manufacturing, and logistics functions are represented by mathematical equations, tabular data, difference equations, and constraints associated with the design variables.

The power of this particular tool is its flexible input formats and solutions formats, permitting its application to problems characterized in conceptual design and continuing through preliminary design. Both analysis and synthesis/optimization may be accomplished for arbitrary definition of the dependent and independent variables.

An example of a design-to-cost solution computed for a small maneuverable aircraft family is shown in Figure 5. It relates dependent variables of "fly away cost", "wing maneuver loading", "wing reference area", and aircraft "cruise radius" to an independent variable associated with a "conventional" or "advanced" manufacturing process.

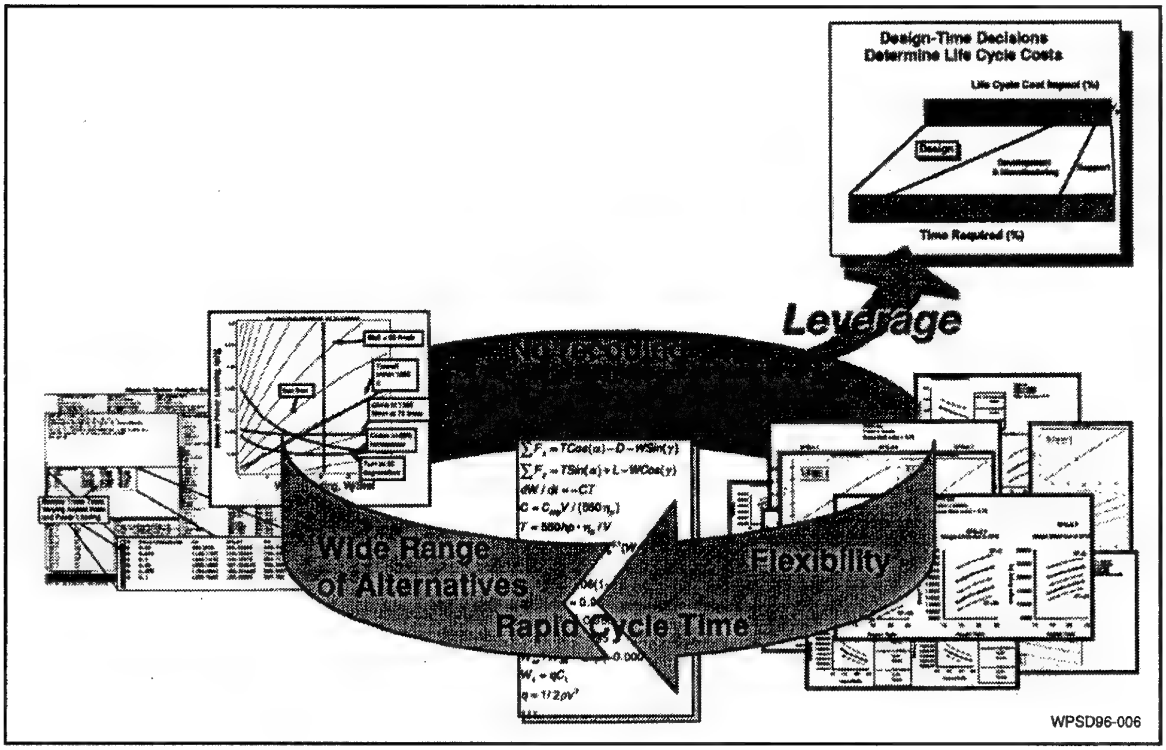


Figure 4. " Design to Cost" Tool

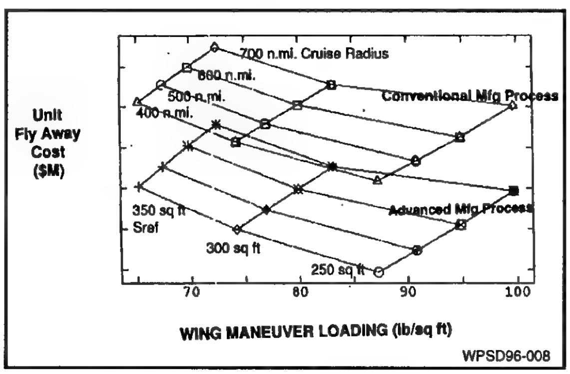


Figure 5. Light Aircraft "Design to Cost" Trade Study for Two Manufacturing Methods

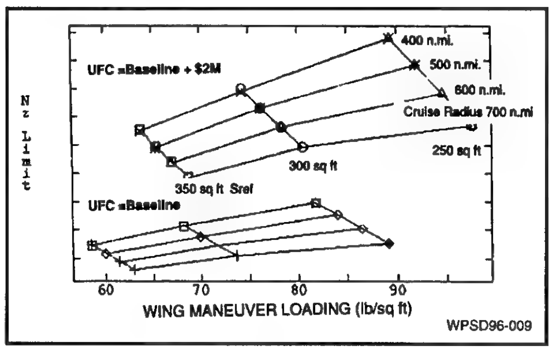


Figure 6. "Design to Cost" Performance Trade Study

A second example of design-to-cost for the same aircraft family and data set is shown in Figure 6 for the independent variable of "unit fly away cost (UFC)". Here the "Nz limit" load, "wing maneuver load", "wing reference area", and aircraft "cruise radius" are the dependent variables.

Key structural data expected at the end of the preliminary design phase are:

1. Increased fidelity FEM of selected configuration
2. Flexible external loads with increased number of cases
3. Structural sizing including flutter, acoustics, fatigue, thermal. May also include AAW optimization
4. Assessment of potential non-linear dynamics phenomenon (limit cycle oscillations)
5. Definition of geometry of substructural members and secondary structures

2.3 Final Design to Translate Configurations to Approved Build-To Packages

The final design phase generally consists of a deeply focused discipline effort in the team context of IPPD. This

is the creation of drawings and stress reports for individual structural components, the development of assembly drawings, the specification of manufacturing processes and test plans, the demonstration of technology readiness, and the negotiation of supplier purchase agreements for equipment and services. At this point the assumed or estimated LCC become negotiated costs for test, manufacture, operations and support.

Key structural data available at the end of final design are:

1. Build to print structural drawings
2. Final sizing analyses
3. FEM's correlated with ground test data
4. External loads validated with test data

3. FORMALIZATION OF THE ROCKWELL "AFFORDABLE SYSTEMS OPTIMIZATION PROCESS (ASOP)"

The process of conceptual, preliminary, and final design in a distributed design environment may be summarized in Figure 7, where optimization includes both cyclic interaction processes as well as mathematical procedures of the calculus of variations. By its title we recognize its inclusion of LCC as a primary design variable along with those traditionally associated with engineering, manufacturing, operations and support.

The ASOP begins with a recognition that the customer's needs are paramount in all product development efforts, but are subject to refinement as a better appreciation of the product occurs. The "quality function deployment" procedures are used to capture and document the requirements necessary for realizing the product. Next a concept is formulated which explicitly and implicitly captures cost associated with requirements, design, manufacturing and operations and support. Depending on the completeness and accuracy of the data, multi-disciplinary optimization may be attempted using the procedures discussed in Section 2. The objective is to arrive at a product satisfying the requirements which "satisfices", meaning the uncertainty and inaccuracy of the design data requires the avoidance of a narrowly defined optimum; the solution must be "robust" to uncertainty. The solution must also minimize risk for continued development. The Taguchi method for design of experiments may be used to minimize the number of analyses conducted, while still capturing the design features necessary to make conclusions and executive decisions. A failure to meet these goals requires a modification to the concept.

Throughout this process statistical process control is employed to parameterize the quality of the engineering, manufacturing, operations and support data. Maintaining these data within tolerances promotes the development of a quality product for the customer. Occasionally the product requires such close tolerance that it may not be designed, manufactured and supported within the tolerances the customer can support. When this difficulty is recognized, changes in requirements or acceptance of additional operational risk may be required. Openly parameterizing these issues for the customer, as part of the ASOP procedures, ensures a maximum operational utility may be reached at acceptable schedule, cost, technology, performance and reliability risks.

3.1 Automated Structural Analysis

Figure 3 previously showed the importance of reducing the structural analysis cycle time. The purpose of Rockwell's initiative for evolving automated Structural Analysis Capability is to reduce design cycle time, tie structural trades to cost models and manufacturing models through the "Design to Cost" methods described previously, and increase design fidelity earlier in the design cycle to reduce redesign and manufacturing re-work.

Automated structural analysis has four major systems:

1. Automated Structural Analysis Process (ASAP);
2. COMETRAN pre/post processor;
3. Active Aeroelastic Wing Optimization Process (AAW);
4. CFD Aeroelastic/flutter/active control analysis system (ENSAERO). To a certain extent, these analysis systems are interlinked to each other through data translators or common analysis models under the ASAP system.

3.1.1 Automated Structured Analysis Process (ASAP)

ASAP is an evolving software based process for rapidly designing aircraft structure from conceptual through detail design (Figure 8). ASAP integrates or links company developed codes with commercial software on a networked computing system through a common master data base.

This promotes structural design cycle time reduction based on continuous process improvement in an integrated product development environment.

The master data base is designed to address the problem of enabling the various analysts to keep abreast of changes in the entire design data base and be able to store, retrieve and manage the data electronically. The integrated process development team establishes the contents of the data base. The ASAP architecture enables the users to retrieve the data from a customized, ICON driven user interface accessible through personal computes and work station computers.

Summaries of various categories of data are stored in "Storyboards". For example, the "Stress Storyboard" is an electronic image containing information needed to identify all of the contents of the stress analysis activities of a subcomponent or subassembly such as a landing gear. The

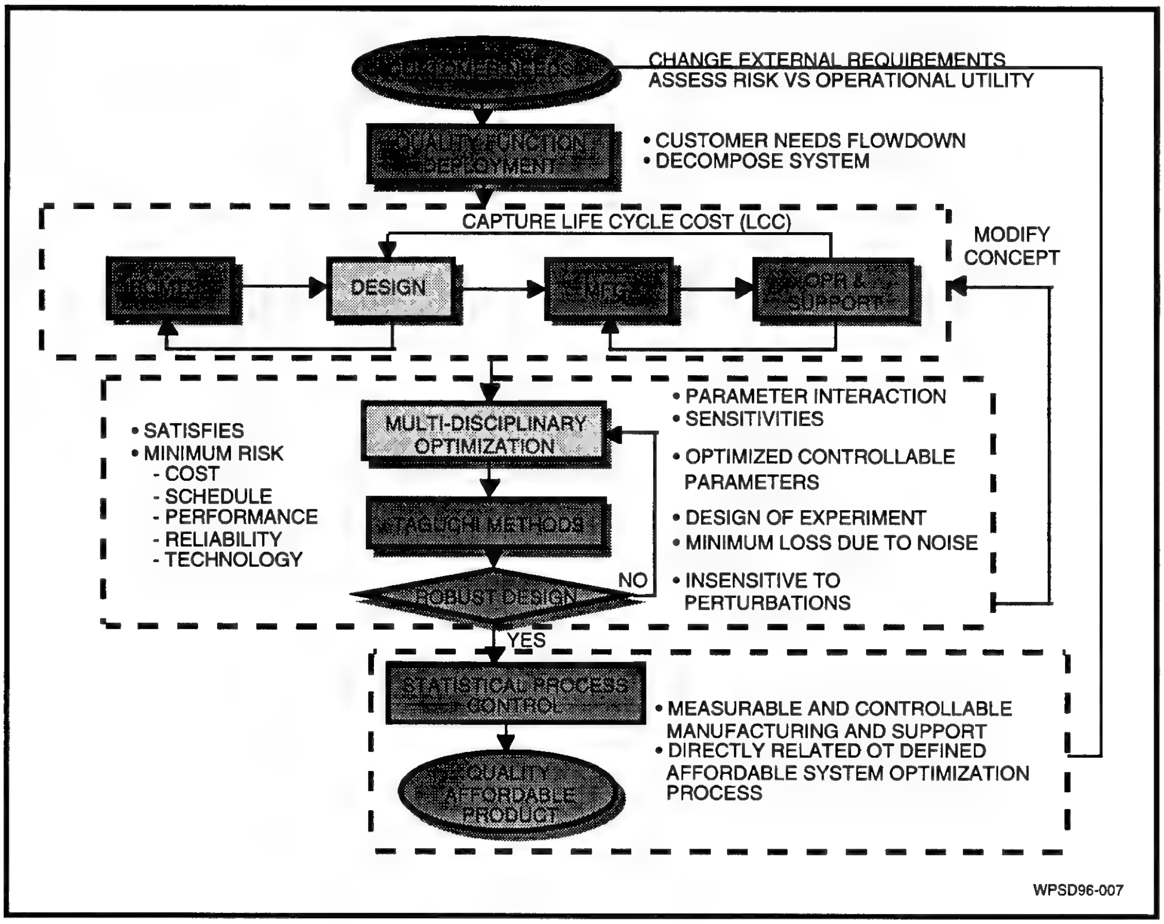


Figure 7. The "Affordable Systems Optimization Process" (ASOP) is Used in All Design Phases

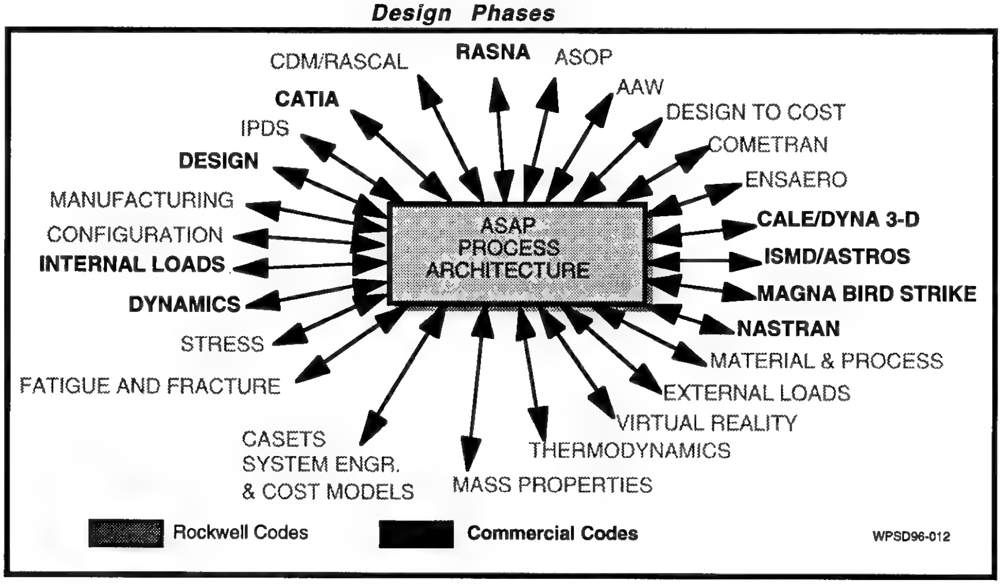


Figure 8. The Automated Structural Analysis Process (ASAP)

storyboard includes a drawing of the component, list of detailed drawings, lists of stress analysis reports, associated requirements documents, etc. The storyboard is updated as new data is electronically approved by the data configuration team leaders. Other categories of data stored in individual storyboards include CAD, internal loads, dynamics, weights, schedule, reviews, etc.

ASAP is designed to enable the interface of company developed codes (such as for FEM preprocessing, external loads, CFD, fatigue, and automated stress analysis) with government and commercial codes (such as CATIA (CAD), I-DEAS, (Pre/Post processing), ASTROS optimization, and NASTRAN). This interface enables rapid transformation of data between the various codes to reduce analysis cycle time.

Progress in reducing analysis cycle time and improving aircraft design performance is illustrated in Figure 9. Rapid finite element modeling techniques to automate FEM generation within CATIA geometry using company developed protocols defined in I-DEAS Master Series have resulted in 60% reduction in model generation time. This has enabled FEM based weight trade studies to be performed in the early stages of the conceptual design phase. (This FEM generation performance has recently been dramatically enhanced by the COMETRAN code, described later).

Integrated stress analysis (Figure 10) links the internal loads from FEM solvers into personal computer spread sheets that are a library of detailed stress analyses for various constructions such as skin-stringer, sandwich construction, etc. As was shown in Figure 9, this has reduced detailed stress analysis time by 50%. Detailed crack-growth geometric element analysis cycle time for complex parts has been improved by using the RASNA modeler/solver for parts especially amenable for solid modeling.

3.1.2 COMETRAN Pre/Post Processor

COMETRAN is a modular based, interactive software pre/post processor system developed by Rockwell, Alpha Star Corporation, and NASA Langley that automates the transformation of CFD generated pressure forces from the CFD grid to the FFM, generates CFD based flexible external loads, automates FEM generation, and enables rapid variational structural trade studies through semi-automated FEM modification. COMETRAN models are exported to other solvers such as NASTRAN and CFD codes.

Figure 11 shows an intermediate transformation beaming grid between the CFD and FEM grids of a commercial transport aircraft, that was automatically generated by the COMETRAN pattern distribution module.

This grid transformed CFD generated forces to the FEM to enable the rapid generation of non-linear, flexible external loads. Four beaming methods are options; each is suited to different levels of model complexity reflecting conceptual, preliminary, or detail design level fidelity requirements.

COMETRAN's rapid FEM generation and variational design capability is illustrated in Figure 12 for a transport fuselage. A structued surface grid model with grid lines specified at potential frame, stringer, longeron, floor, and large hole locations is generated based on CAD geometry. The user simply defines type of construction of the skins and substructure (I-beams, J section etc.) and the initial member sizes (web depth, cap width, etc.). COMETRAN then automatically generates the grids and elements of the

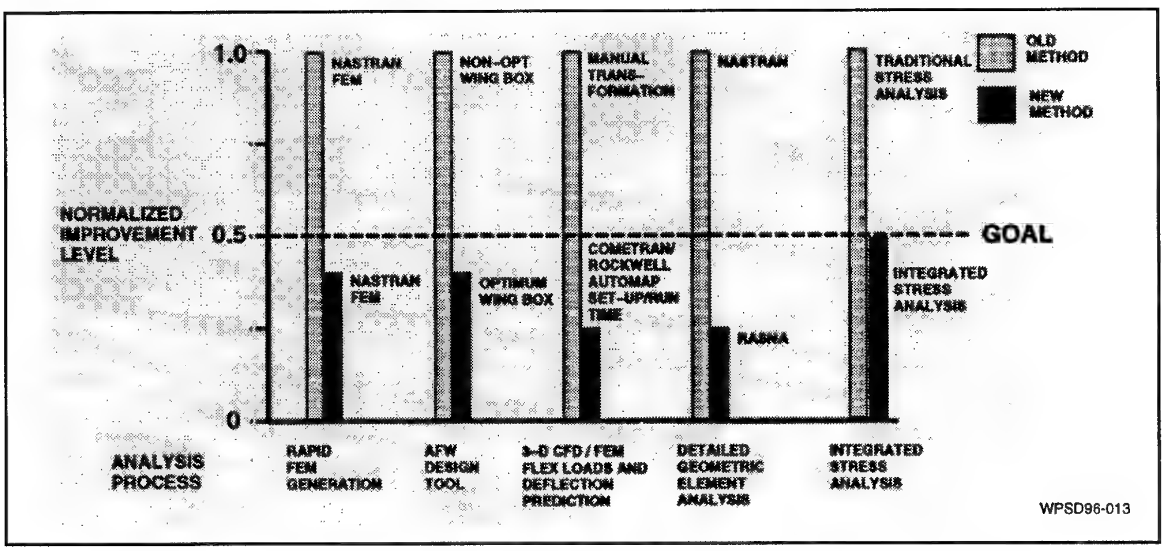


Figure 9. ASAP Progress in Reducing Modeling and Analysis Cycle Time

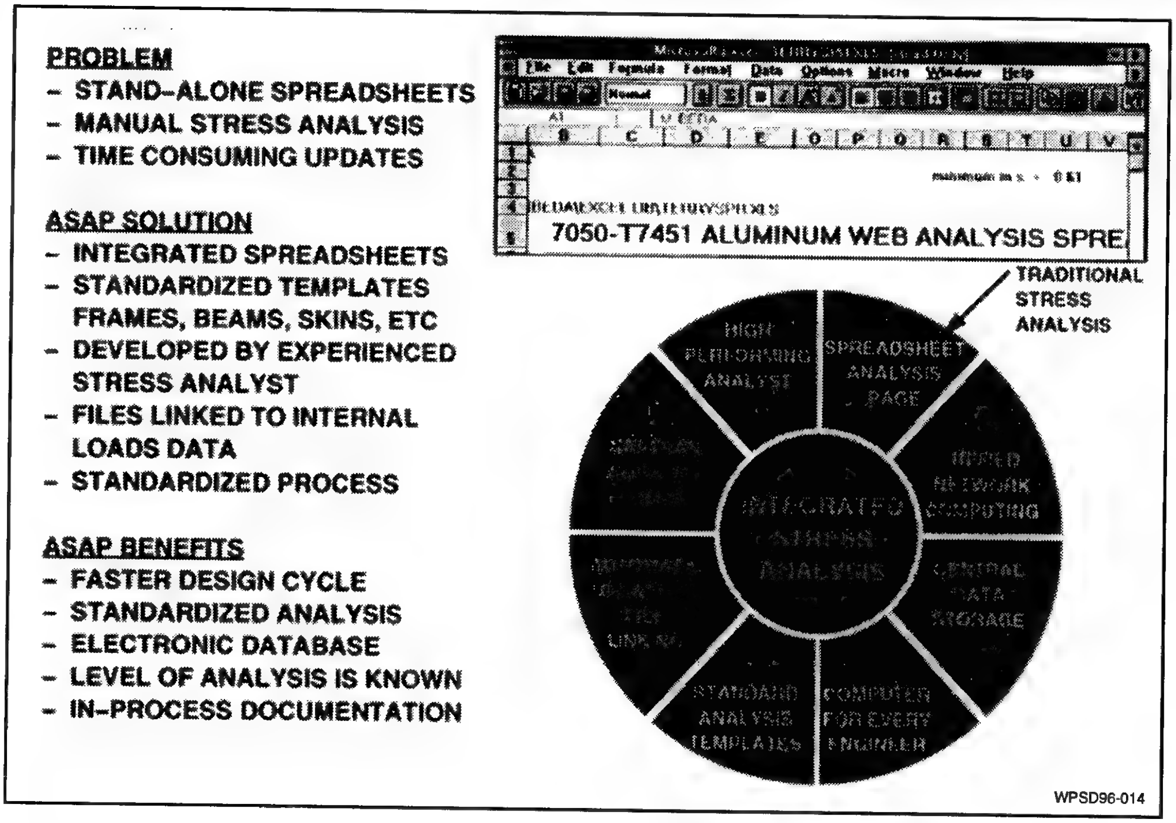


Figure 10. ASAP Integrated Stress Analysis Key Characteristics

structural members. The size and location/spacing of the members can be easily and rapidly changed by simple user commands or menu picks for trade studies. COMETRAN then automatically "punches holes" in the structure at user defined locations to accommodate windows, doors, and access.panels. The entire fuselage FEM shown in Figure 12 was generated in 20 minutes, which is a drastic reduction in generation time compared to traditional methods.

Changes in aircraft configuration (sweep, span, wing attachment location) can also be quickly accommodated by COMETRAN. For example, if the wing sweep angle is changed, the program automatically updates the FEM grid, as shown in Figure 13.

3.2 AAW Optimization

Active Aeroelastic Wing (AAW) technology is a multi-disciplinary, synergistic technology that integrates air vehicle aerodynamics, controls, and structures together to maximize air vehicle performance by allowing thinner, higher aspect ratio wings that are aeroelastically deformed into shapes for optimum performance.

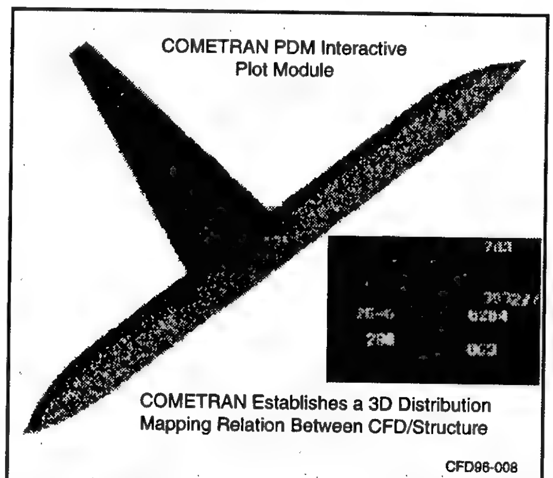


Figure 11. COMTRAN PDM CFD to FEM Transformation

AAW technology uses wing aeroelastic flexibility for a net benefit. Wing control surfaces are used as "tabs" that promote wing twist instead of trying to negate it. The power of the air stream (e.g., flight dynamic pressure) is

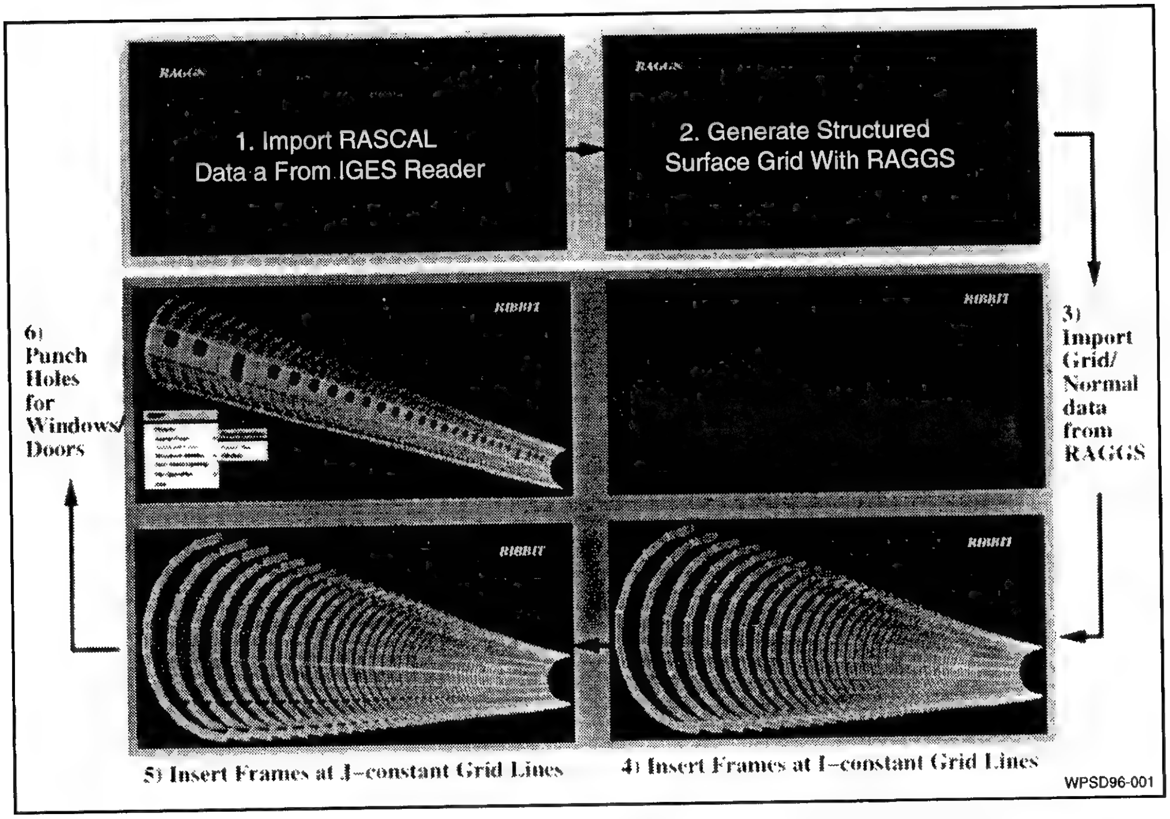


Figure 12. ***COMETRAN's Rapid FEM Generation and Modification***

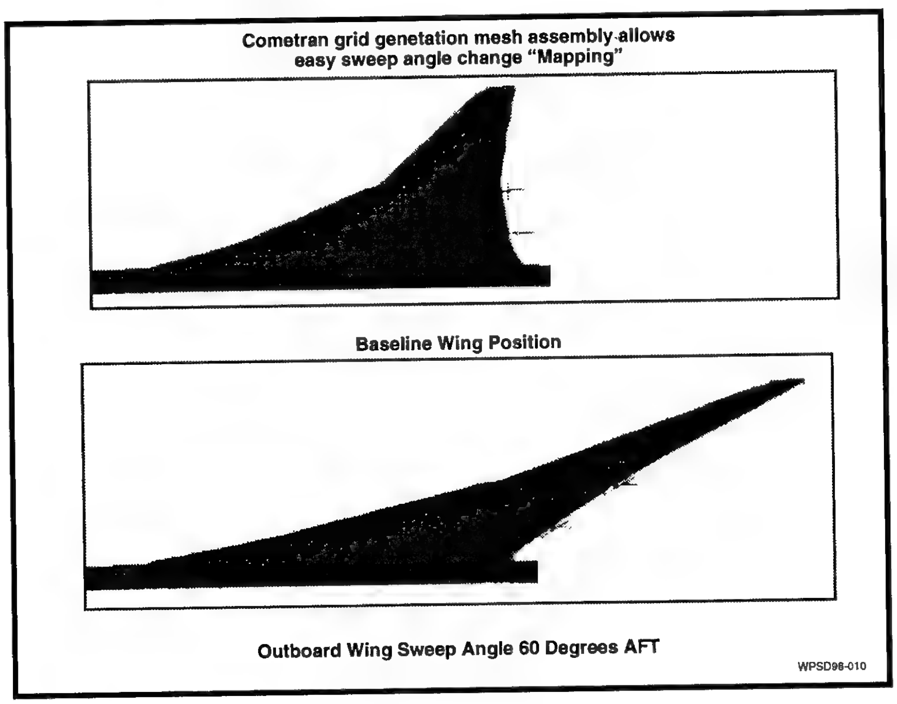


Figure 13. ***COMETRAN Enables Rapid Configuration Changing in the FEM***

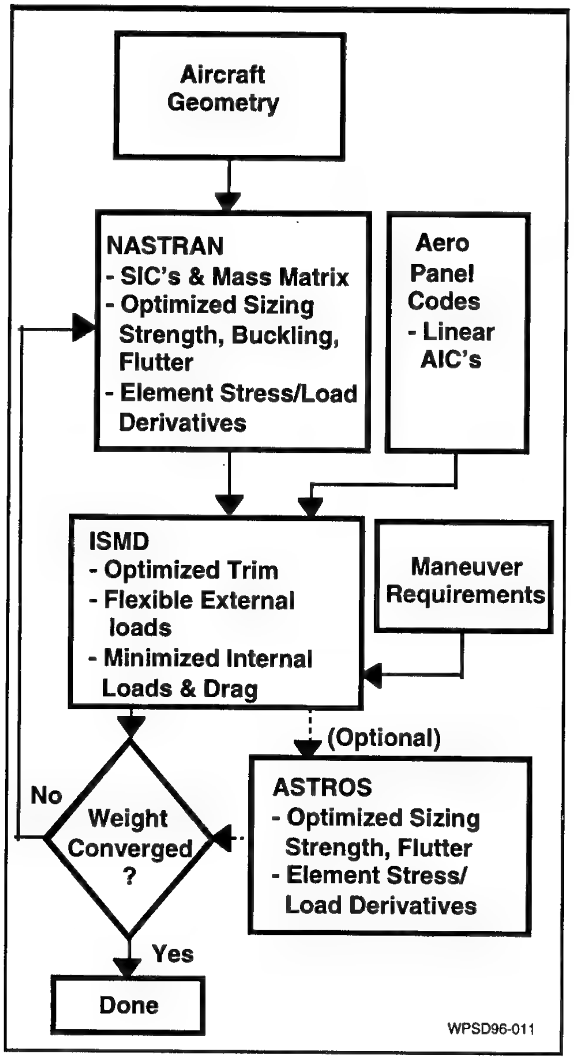


Figure 14. AAW Design Process

employed to twist the wing with very little control surface motion. The wing twist creates the control forces in AAW technology. When correctly applied, an AAW wing will actually twist less than a conventional "rigid" wing that twists in opposition to the control force generation.

AAW provides very large control power that can be used for multiple purposes such as: twisting the wing into a shape for minimum drag at multiple flight conditions; twisting the wing to provide maneuver control power for rolling or pitching the air vehicle; and twisting the wing to minimize the structural loads, thereby reducing structural weight or allowing higher aspect ratio wings.

Therefore, an AAW design process is required which couples aerodynamics, structures, and external load designs together. This design process must also include the flight controls discipline, to assure that the resulting design may be implemented within a digital flight control system. this process allows for coupling between structural variables, aerodynamic design variables, and control surface trim variables, while satisfying structural and trim constraints. It simultaneously optimizes the structure and aerodynamic performance.

Figure 14 shows that the AAW design process uses a NASTRAN finite element model to generate structural influence coefficients and a mass matrix that is input into Rockwell's Integrated Structure/Maneuver Load design (ISMD) module. ISMD generates trimmed, aeroelastic external loads for multiple design maneuver cases by determining the schedule of control surface deflections that minimize the wing stresses and drag while meeting maneuver requirements (max roll rate, Nz max, etc.). These loads are then input into NASTRAN or optionally into the ASTROS code, which re-sizes the structural gages by performing minimum weight optimization analyses for strength, flutter, and buckling. The cycle is then repeated until weight convergence is achieved, as shown in of Figure 15.

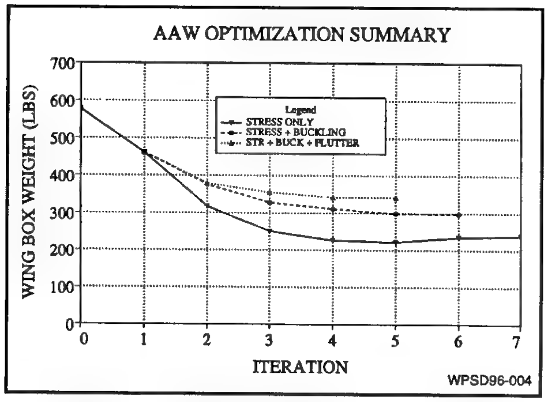
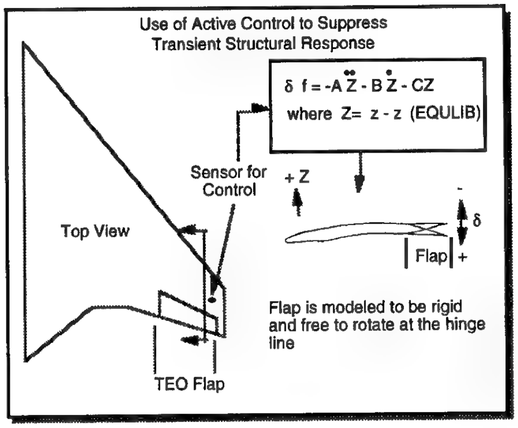


Figure 15. Typical Fighter Wing Weight Reduction Using AAW Design Process

3.3 CFD Aeroelastic/Flutter/Active Control Analysis

Due to analytical tool limitations, non-linear aeroelastic oscillations of lifting surfaces and destabilizing transonic effects on classical flutter are usually not investigated until the detail design phase using wind tunnel models or flight test. These phenomenon can be caused with unsteady vortices, shock waves, and separating/reattaching flow fields. Design methods to prevent or delay these phenomenon may require adding stiffness and weight to the vortex structure, adding external aerodynamic devices (vortex generators, bumps, chines, etc.), imposing flight condition limits on the aircraft flight envelope, or adding an active control system suppression system, which all



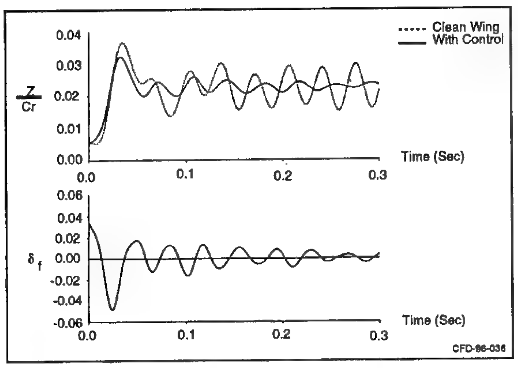


Figure 16. CFD ENSAERO Code Simulates Active Control of Non-Linear Flutter with Adverse Shock Effects

could require significant development cost and adverse schedule impacts. Therefore, assessments and design resolution of these potential problems early in the preliminary design phase can reduce program risk and cost.

Rockwell is engaged in the development of CFD based aeroelastic analysis tools that can predict non-linear limit cycle oscillation and transonic shock effects or flutter, by enhancing the ENSAERO CFD code. This capability extends from Euler to thin layer Navier-Stokes methods for modeling unsteady shock waves and vortex flows. Figure 16 illustrates an ENSAERO unsteady aeroelastic simulation of an upper surface transonic shock wave coupling with the bending mode response decay of a fighter type wing. The reduction in the modal damping due to the adverse phase of the shock motion relative to the bending mode deflections is stabilized by the addition of a simple aileron feed back control suppression law, simulated in ENSAERO. Thus, this tool can be economically used in the preliminary and detail design phases to help guide the aircraft dynamic design.

Conclusions

Integration of automated structural analysis and design processes with "design-to-cost" tools is paramount for producing affordable aircraft systems. Rockwell's approach for this multidisciplinary integration is the development of an "Affordable Systems Optimization Process" (ASOP) which includes four automated structual analysis systems and a "design-to-cost system". A key goal is to enable "preliminary design" quality at "conceptual design" speeds. This process has been applied to various aircraft conceptual, preliminary, and detailed design stages, and has shown capability to reduce design cycle time and determine optimal of "best value" system cost.

A SIMPLIFIED APPROACH TO THE MULTIDISCIPLINARY DESIGN OPTIMIZATION FOR LARGE AIRCRAFT STRUCTURES

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Manuel Huertas
José Carlos Gómez

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1. SUMMARY

The last tendencies in optimization indicate that in early design stages, it is necessary to perform multidisciplinary analysis for designing large structures. This paper presents the simple but very efficient tool that CASA is using during the preliminary stages of the aircraft structural design for defining and selecting the structural characteristics.

The development of this software package, ALACA, was undertaken by CASA Engineering Directorate in the last years for the purpose of designing the composite wing of CASA 3000 Aircraft. ALACA optimizes wing structures satisfying all the structural requirements (weights, static loading, material, fatigue, residual strength, manufacturing, flutter, etc.). The main advantages of the program is the no necessity of finite element techniques, that make it easier than other available codes and allow it to be used in the earliest phases of the project (preliminary design) before freezing the general arrangement of the structure. The results from the CASA 3000 studies show the reliability and efficiency of ALACA as a design tool.

2. INTRODUCTION

In the preliminary design phase, the basis for the wing general arrangement must be established as early as possible. This means, to select the optimum configuration for the wing lay-out parameters: stringer pitch, profile depth (t/c) and rib spacing before the final design is decided. In addition, the determination of the minimum wing masses involves a study of the wing structure by reducing weight at an affordable cost while the strength and stiffness requirements are maintained. In order to achieve the most efficient wing structural design, a large number of different structural configuration might have to be analyzed rapidly before a particular configuration is frozen for detail design. This process is called wing optimization.

The CASA approach to this optimization process is done by means of an advanced analytical tool called ALACA, valid for all kind of lifting surfaces: wings and empennages. The main advantage of ALACA is that the finite element techniques are not required, being the usage simple and friendly and the input time preparation very reduced.

This paper presents the ALACA capabilities and its potential application to the design of a torsion box. ALACA is a users friendly package for three purposes:

- Getting stresses and strains for the torque box.
- Achieving a redesign of the structure for reducing weight.
- Performing a complete structural justification, both static and fatigue, of the torque box.

and it is used by the designer to facilitate the

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configuration selection and the evaluation of alternative concepts during the predesign of an aircraft.

The procedure described here, has been developed by CASA Engineering Directorate over the past years:

- An algorithm called ALA using the beam bending and torsion theories for analyzing torsion boxes under external applied loads was developed in the 80's (Ref. 1).

- An initial optimization capability and some buckling analysis was included in ALA in 1991 in a pilot version for the design of simple metallic wing box. Experience gained with this pilot code suggested in 1992 to incorporate composite skins and manufacturing, fatigue, and flexibility constraints (Ref. 2). In that moment the ALACA tool was generated and applied for the first time in CASA 3000 composite wings. Very recently new features have been incorporated: design variable linking, residual strength analysis, and further improvement of buckling checking. The result of these additions an efficient preliminary design tool, integrating numerous strength and stability analyses into one computer program that requires minimum input data and which is economical in computer cost.

3. GOALS

Wings and horizontal stabilizers are those parts of the aircraft with the most free parameters and therefore they are a complex task for optimization. Theirs weights are dominated mainly by the primary structure since the torsion box represents between 60% and 70% of total lifting structure weight.

The sizing of the primary structure of a lifting surface during the preliminary design phase has to be as fast and accurate as possible to encompass continually changing studies performed by different disciplines simultaneously.

In this stage, only preliminary data are available and therefore used. Hence, the use of simple but powerful computer programs which provide fast answers to design changes with a high level of accuracy is inevitable. This kind of software tool called ALACA has been developed for the evaluation of torsion box designs having the purpose of providing the users with an optimum sizing of a tapered multicellular torsion box (fig. 1) under different load cases for an overall minimum weight and with the following requirements:

- Automatic generation of the structural model based on minimum input.

- Capability of calculating different structural layouts as for example: multispar concepts, open torsion box cross-section, etc.

- Separate identification of individual parts of the torque box, shells, stringers, spar caps and spar webs.

- Capability of considering both metallic and composite materials.

- Capability of handling most of important manufacturing and production requirements.

- Reduced computer consuming time with accurate results.

- In-service repair limitations can be easily considered.

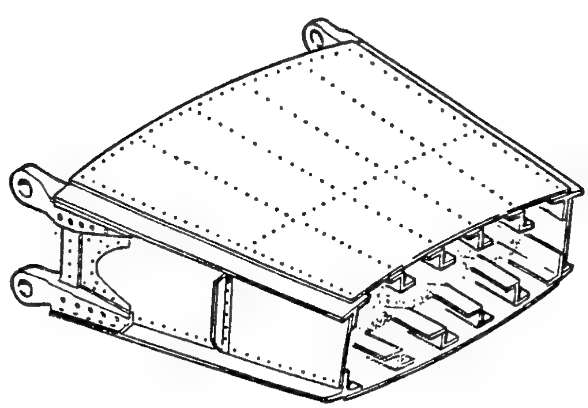


Fig. 1: Torsion box typical configuration

4. PROGRAM BASIC CONCEPTS

As above mentioned the purpose of the ALACA code is to provide the users with an optimum sizing of all the constitutive structural elements of a tapered multicellular torsion box. Optimum sizing

means here the dimensions of different structural elements that lead to a minimum overall torque box weight fulfilling the structural integrity and additional requirements imposed by the user. The overall structural weight is determined by adding the cover weights, the spar weights and the rib weights.

The rib weight is mainly driven by externally applied forces such as control surfaces and flaps, wing to fuselage connections and engines and landing gear attachments. These locally applied loads are generally unknown on the preliminary design phase although their global effects on the structure are accounted for. Discounting these local effects the rib weight required to support the cover is about 5 percent of the total cover weight and usually the minimum gauge satisfies this requirement. Based on this assumption, only the weights of the covers and the spars, i.e. the bending material weight, are optimized. The objective function defined is the minimization of the bending material weight, considered as the addition of covers plus spar weights.

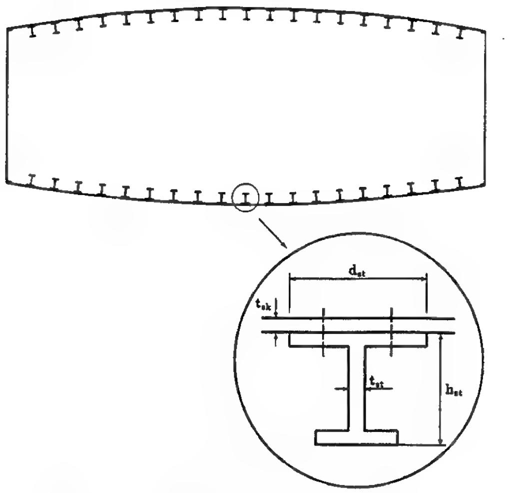


Fig. 2: Design variables definition

Design variables are the dimensions of the structural elements that constitute torsion box cross-section. This is, panels thickness, stringer thickness, stringer height, stringer foot width, spar cap thickness, spar cap height and spar web thickness. A special feature of ALACA to be noted is its capability to handle stringer dimensions as separate design variables (stringers are not considered as lumped elements having area and inertia but their dimensions are optimized in order to achieve the tool target). This allows users to impose manufacturing and repair constraints easily apart from obtaining directly the optimum stringer configuration. (Fig. 2)

As it is well known, in the optimization process the number of design variables has to be limited not only for computer resources but also for practical reasons. It is impractical and unnecessary to retain each element in a large structural model as an independent design variable. Inside each torque box section, ALACA allows users:

- To include any number of structural element dimensions into the same design variable.

- To establish linking between these design variable reducing the total number of them. Design variable linking is accomplished by linear relationship among design variables.

- To keep fixed the dimensions of some structural element during the optimization process.

All these features in design variable linking enable users to impose directly production requirements and make easy the final results engineerization. So that, for example, a composite wing skin could have panel thickness as design variable for each individual panel between stringers but limiting thickness difference between adjacent sub-panel, or stringers could be grouped into families as typical for composite applications. Thus, in the first case, during optimization the thickness of each sub-panel varies independently but keeping the difference in thickness between adjacent sub-panels lower than the ply-drop-off thickness allowance given by the user.

Presently, ALACA optimizes torsion box structures subject to the following constraints:

- Global or overall buckling of the skin-stringer combination under combined loads.
- Local skin buckling under combined loads.
- Stringer/spar cap crippling.
- Stress and strain design criteria.
- Fatigue stresses.
- Pseudo-aeroelastic constraints: $GJ > k(EI)$ and/or $GJ > K$.
- User's input constraints given as linear relationships $g(x_i) < 0$ where x_i are design variables.
- Minimum reserve factor for the structure and, if skin postbuckling is allowed, minimum reserve factor for local skin buckling.

Damage tolerance considerations are just now being implemented into ALACA. Specifically, the tension two bay crack criterium for metallic structures will be ready in the nearest future.

The maximum size of the problem which can be solved is given by the following parameters:

- Independent design variables: 400
- External loading cases: 10
- Total number of constraints: 4200

The architecture of ALACA is modular with each logical task forming a differentiated module. The modules are linked together through a control program. Most of these modules or subroutines are forming part of CASA packages for structural strength analysis. If required, they can be easily substituted by other subroutines with the same purpose. Apart from the input data module, three are the major modules:

- The stress analysis module
- The strength analysis module
- The optimizer module

The stress calculation of the torsion box is based on the assumption of an elementary beam with an elastic behaviour and uses the theory of multicellular shells/cross sections (Ref. 3).

The strength module is based on current CASA strength analysis packages in some cases slightly simplified in order to reduce the computing time.

The optimizer is based on the modified method of feasible direction.

The ALACA flow chart is shown in figure 3. In an optimization iteration, the stress analysis and the strength checking are performed with the current structure. After constructing numerical constraints, active and violated constraints are identified and their gradients (sensitivities) evaluated. The optimizer selects a new structure which tries to minimize weight and satisfy the violated constraints. The iteration continues until mathematical conditions of minimum are reached or until all constraints are satisfied and the weight variation is stationary.

5. INPUT DATA MODULE

The input data module defines the geometrical model of the torque box to be optimized and the structural model with all data needed for the complete definition of the problem (design variable definition, constraints, materials, loads, etc.).

The model is an assembly of a number of partial wing box elements. Each one of these portions is defined by the specification of the two end cross-sections indicating the location of the section plane in a basic reference coordinate system (Z coordinate) and the position of each stringer (and spar caps) into this plane (X and Y coordinates of intersection points between stringer position and LOFT surface). The position of intermediate spars is given separately. A complete definition of the torque box is obtained by automatic linear interpolation between the entered wing stations. Thus, a tapered multispar torque box having different number of stringers in the end sections can be fully described. The geometrical model, is completed with the rib spacing data.

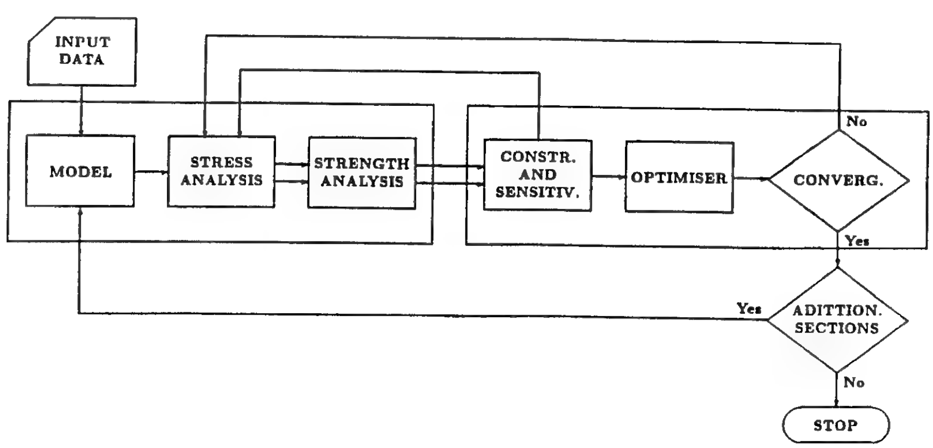


Fig. 3: ALACA flow chart

The cross-section shapes of the upper and lower stringers are chosen from a stringer shape data base. Table 1 shows the current available cross-section shapes together with the stringer dimensions which can be taken as design variables for each stringer type.

There are four available stringer shapes for composite materials and eleven stringer shapes for metallic materials. It has to be noted that some manufacturing constraints are already included in the proper shape definitions, for example, stringer shape type 1 follows the A330/340 HTP stringers construction where the T-shape is obtained from two L-shape hot-formed CFC laminates. This construction leads to a stringer where the foot thickness is half of web thickness.

The structure model is completed given a pre-dimensioning of all structural elements, this is, panel thickness, and stringers and spar caps dimensions according to the stringer chosen shape.

This pre-sizing can not satisfy the constraints, but a set of good starting values will reduce the number of iterations required to convergence, and will avoid divergence problems and will conduct the objective function to the minimum. Except for near-fully constrained design, the experience using ALACA and numerical optimization says that different optimum designs (different stiffening ratio) having the same minimum weight can be reached depending on the starting values. Therefore, the importance of a good starting point to conduct the process to the desirate design (adequate stiffening ratio for damage tolerance).

ALACA can handle both isotropic metallic and orthotropic composite materials. In any case, average and allowable material properties have to be entered because the stress analysis of the structure (internal load/stresses) is performed with average mechanical properties and the structural strength analysis make use of allowable mechanical properties.

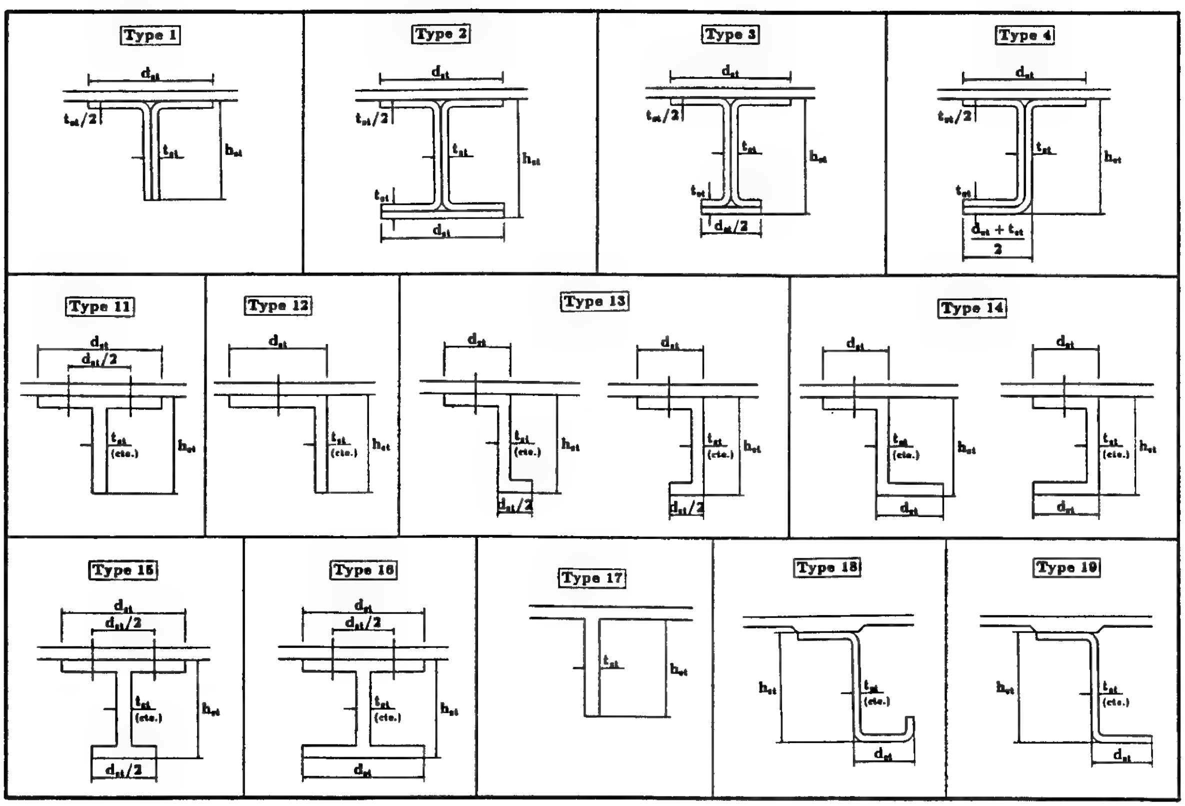


Table 1: Stringer shape data base

For metallic materials, if plasticity effects need to be taken into account, an additional datum is requested: the stress-strain curve shape parameter, n, as defined by Ramberg-Osgood.

The degradation in properties due to fatigue and/or life cycle effects for metallic materials and due to damage tolerance considerations (maximum fibre strain corresponding to barely visible impact damage) are entered at this point of the input data process. Finally different materials can be specified for upper skin, lower skin, upper stringers and lower stringers.

External loading applied to the torque box is defined given the six components of the resulting load for each load case at two wing stations in a load reference coordinate system to be specified by the user. As for the geometric model, loads acting on intermediate stations are calculated by linear interpolation between the entered values at ended stations.

Design variable definition is established specifying an integer number (design variable code) for each structural dimension. Dimensions with the same code are associated with the same design variable. Structural element dimensions not associated with any design variable (design variable code zero) are considered fixed during the optimization process (dimensions not to be optimized). Apart from structural performance requirements and the limits for the design variable variation (upper and lower bounds), users can specify additional constraints in the form of linear relationship among design variables such as $g(x_i) \leq 0$, x_i design variable i. This way is very useful to impose manufacturing and in-service repairs to the structure. Thus, a typical constraint introduced in CASA design of composite skin stiffened by T-shape stringers is to provide enough stringer height and stringer foot width to allow repair in service using riveted metallic angles. Assuming that the diameter of the rivet to be used in the repair is equal to the stringer thickness, this constraints will be read as follow:

$$5x_i - x_j \leq 0$$

where x_i is the design representing the stringer thickness and x_j the stringer height respectively.

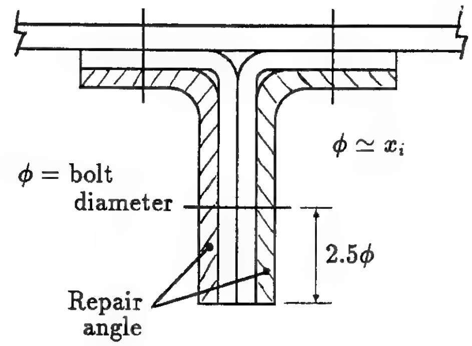


Fig. 4: Typical stringer with a repair

Finally, the input data is completed entering the minimum reserve factor for the structural performance requirements (minimum allowable load to internal applied load ratio) and, if skin postbuckling is allowed the minimum reserve factor for local skin buckling (percentage of ultimate load beyond local skin buckling is allowed).

6. STRESS ANALYSIS MODULE

The stress calculation of the torque box is based on well known classical bending-torsion theories (Ref. 3). These are the elementary theory of bending with the assumption of Navier and Bernoulli. The theory of Bredt-Batho and Saint Venant for torsion of thin walled multicellular cross-section is followed. Detailed description of these theories can be found in the literature. Basically, these theories assume a constant shear flow in the skin between adjacent stringers and add the direct stress carrying capacity of the skin to the existing stringers/booms areas by means of equivalent areas. The calculation of these equivalent areas is controlled directly by the users through individual correction factors to account for spar webs, existing man-holes, non-effective reinforcement and so on.

The stress analysis performed by ALACA account for tapered torque box in both spanwise and chordwise directions. Also the correct position of the stringer plus skin area centroid (which is a function of stringers shape and dimensions) is considered into the analysis instead of the geometrical model data.

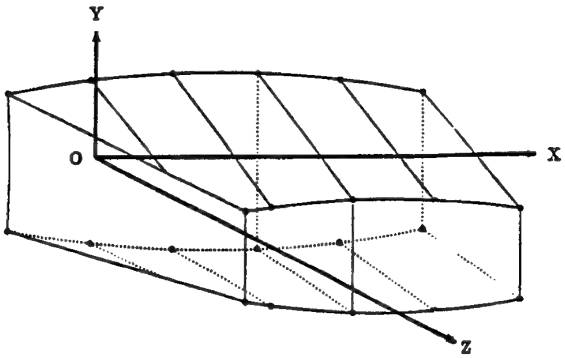


Fig. 5: Stress analysis model

Under all these considerations, the direct stress system for a torque box section (Fig. 5) is given by the following equation in which the coordinates and the sectional properties are referred to axes with the origin at the centroid of the direct stress carrying area.

$$f_z=-\frac{M_y(EI)_x+M_x(EI)_{xy}}{(EI)_x(EI)_y-(EI)_{xy}^2}E_x+\frac{M_x(EI)_y+M_y(EI)_{xy}}{(EI)_x(EI)_y-(EI)_{xy}^2}E_y+N\frac{E}{(EA)}$$

The shear flow due to torsion is calculated neglecting the warping due to torsion (no axial constraints effects are present and the shape of the wing section remains undistorted by the load application). Under these assumptions, the torsional moment results in a constant shear flow along the contour of the multicellular cross-section of the profile. From the equilibrium of the torsion moment:

$$M_t=2\sum_{R=1}^{N} q_R\, A_R$$

The rate of twist of each cell of the cross section must be identical.

$$\left(\frac{d\theta}{dz}\right)_R=\frac{1}{2A_R\bar{G}}\oint_R\frac{q_R}{(G/\bar{G})t_R}\,ds$$

$$\left(\frac{d\theta}{dz}\right)_1=\left(\frac{d\theta}{dz}\right)_2=\dots\dots=\left(\frac{d\theta}{dz}\right)_N$$

A linear equations system is achieved to be solved for the N unknown values of shear flow q_r and the one unknown value of $d\theta/dz$.

The shear flow due to transversal force for a section with closed cells is a statically undefined problem. From the assumption of an undisturbed cross-section, another linear equation system is achieved given the N unknown values of shear flow q_{so} and the one unknown value of $d\theta/dz$. Thus the total shear flow due to transversal force is:

$$q_s=-\frac{Q_x(EI)_x-Q_y(EI)_{xy}}{(EI)_x(EI)_y-(EI)_{xy}^2}\left(\int_o^s Et\;x\;ds+\sum_{r=1}^{n}Br\;xr\right)-$$

$$-\frac{Q_y(EI)_x-Q_x(EI)_{xy}}{(EI)_x(EI)_y-(EI)_{xy}^2}\left(\int_o^s Et\;y\;ds+\sum_{r=1}^{n}Br\;yr\right)+q_{so}$$

With the above algorithms, the following parameters are calculated for each element and so for each cross-section:

- Geometrical parameters of the cross section: areas, inertial moments, bending stiffness, torsional stiffness, etc.
- Neutral axis position and shear center position.
- Normal stresses and strain distribution in the cross section.
- Shear stress distribution due to transversal forces and torsion.
- Twist of the cross section.

7. STRENGTH ANALYSIS MODULE

The strength analysis performed in ALACA determines the allowable stresses and loads for each structural component. Implemented methodologies are based on current CASA strength analysis packages: ARAL package for the analysis of metallic wing structures (Ref. 4) and ARPA package for composite wing constructions (Ref. 5). Subroutines have been taken directly from these packages and in some cases slightly simplified in order to reduce the computing time.

Wing skins are stiffened panels under combined tension/compression and shear. In compression,

local and overall buckling modes are considered.

Local buckling (Fig. 6) is analysed through an energetic formulation following the Rayleigh-Ritz methodology which account for the effect of the stringer torsional rigidity and panel thickness change. Plasticity effects are taken into account for metallic construction. Related to ARAL and ARPA packages a simplification has been adopted here. Instead of calculating local buckling stresses for each panel under all set of loading cases (too expensive when a large number of loading cases are presented) only local buckling under pure compression and shear load are computed being after these values combined through an iteration formula for each loading case.

$$R^{\alpha}_{c} + R^{2}_{s} \leq 1$$

where α varies between 1 and 2 dependent on the strain-stress curve point where local buckling takes place.

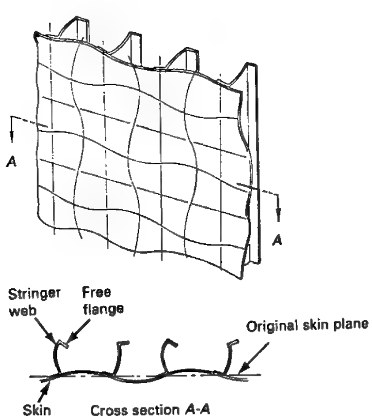


Fig. 6: Skin local buckling mode

For spar caps and stringer crippling evaluation the following formulas are used (Ref. 6):

For metal:

$$\frac{F_{cc}}{F_{cy}} = \alpha_m \left(\frac{b}{t} \sqrt{\frac{F_{cy}}{E}} \right)^{\beta_m}$$

For composite:

$$\frac{\varepsilon_{cc}}{\varepsilon_{pl}} = \alpha_c \left(\frac{\varepsilon_{cu}}{\varepsilon_{pl}} \right)^{\beta_c}$$

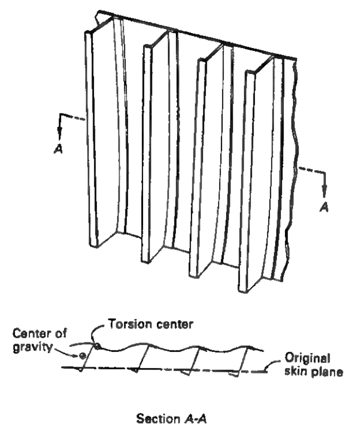


Fig. 7: Overall buckling mode

The overall buckling (Fig. 7) load is found through a column buckling analysis for each loading case. The effective skin width is given by the Von Karman equation:

$$\omega_{ef} = b \sqrt{\frac{F_{pl}}{f}}$$

and both pure flexural buckling (stable stringer cross-section) and iteration of flexural buckling with crippling (non-stable cross-section) analyses are performed (Fig. 8). The flexural buckling load is determined by the Euler-Engesser formula:

$$F_{co} = \frac{\pi^2}{\left(\frac{L / \sqrt{c}}{r_{co}} \right)^2} E_t$$

$$P_{co} = F_{co} A_{co}$$

where the Ramberg-Osgood equation is used for the tangent modulus E_t.

The interaction of flexural buckling with crippling is given by means of a potential function:

$$F_{co} = F_{cc} - \delta \left(\frac{L / \sqrt{c}}{r_{co}} \right)^{\gamma}$$

which satisfy the requirement of being tangent to the Euler-Engesser curve at the local buckling stress of

the weakest stringer element.

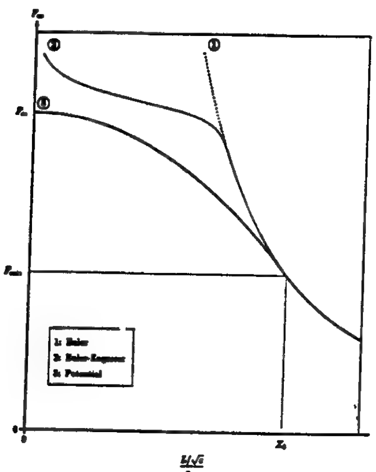


Fig. 8: Euler, Euler-Engesser and potential curves

The lowest of two above buckling loads is taken as column buckling load.

An interaction formula relates the column buckling load with the allowable shear stress of the skin:

$$R^{\eta}_{c} + R^{2}_{s} \leq 1$$

where η varies between 1 and 2 dependent on the compression-shear applied stresses ratio and the point of the strain-stress curve where overall buckling is initiated.

8. CONSTRAINTS CONSTRUCTION

Once the stress and strength analysis of the torque box is performed, the constraints construction is straightforward.

- Structural performance constraints.

  One of the ALACA inputs is the minimum reserve factor (RF_m) for satisfying the structural performance requirement. If local buckling of the skin is allowed another reserve factor (RF_l) for this requirement must be entered. For each loading case, the following structural performance constraints are considered:

  - Overall buckling: $RF_m - \lambda_o \leq 0$
  - Skin local buckling: $RF_l - \lambda_l \leq 0$
  - Strain design criteria: Only for composites

    $$RF_m - \varepsilon_m/\varepsilon_o \leq 0$$
    $$RF_m - \varepsilon_m/\varepsilon_{45} \leq 0$$

  - Crippling: $RF_m - F_{cc}/f_z \leq 0$
  - Fatigue stress: Only for metal

    $$RF_m - \frac{F_f}{\sqrt{f_z^2+3f_{xy}^2}} \leq 0$$

  where λ_o and λ_l are the reserve factors for the current structural sizing in each iteration step, ε_o, ε_{45}, f_z and f_{xy} are applied strains and stresses on current structural elements sizing and F_f is the allowable fatigue stress.

The remainder constraints considered into ALACA are not stablished for each loading case. Pseudo-aeroelastic constraints may be imposed reading as follow:

$$GJ > k(EI) \text{ or/and } GJ > K$$

where GJ and EI are the torsional and bending stiffnesses of the torque box in a station, K is a fixed torsional stiffness and k is a constant. This kind of constraint tries to assure that sufficient torque box GJ is available to prevent wing flutter at a later time.

Finally, users input constraints in any number may be handled by ALACA as mentioned in the input data description chapter.

9. OPTIMIZER MODULE

The optimizer module adopts the modified method of feasible directions (Ref. 7), one of the most reliable and robust direct method algorithm. A special attention has been paid to improve the rate of convergence to the optimum.

Reciprocal design variables z_i are used instead of original or direct design variables x_i:

$$z_i = \frac{1}{x_i}$$

With this technique, the design space is transformed in such a way that the most constraints have a far better linear behaviour despite the fact that the objective function becomes non-linear.

Constraints are normalized in the usual manner. A constraint written as:

$$g_j(z_i) - g_{j\,\max} \leq 0$$

when normalised is written as:

$$\frac{g_j(z_i) - g_{j\,\max}}{|g_{j\,\max}|} \leq 0$$

Constraints screening is carried out to retain the active and violated constraints and only these ones are collected for optimization in each iteration. The governing definitions of active and violated constraints implemented in ALACA are:

$$-0.03 \leq \frac{g_j(z_i) - g_{j\,\max}}{|g_{j\,\max}|} \leq 0.005$$

$$\frac{g_j(z_i) - g_{j\,\max}}{|g_{j\,\max}|} > 0.005$$

The gradient of the objective function and all the active and violated constraints are evaluated by numerical derivation because of the rapid evaluation done by the analysis modules.

Basically, the optimization method implemented in ALACA first finds a feasible design solution if the initial one is unfeasible. In this point determines a search direction in the design space from the objective function gradient, the gradients of the active and violated constraints and the design variable bounds. Once the direction is found, one dimensional search is performed to determine the optimum size to move in the design space. Each step size evaluation requires computing the new objective and constraint values. The optimum step size is selected based on the minimum objective value and constraint violations. Then, the design variables are updated and a new iteration starts. Convergence is achieved when one of the following criteria is satisfied:

- Relative change in the objective function among three iterations is less than a specified tolerance (0.1%).
- Absolute change in the objective among three iterations is less than a specified tolerance.
- The Kuhn-Tucker criteria are satisfied.

10. NUMERICAL EXAMPLE

The design exercise is to optimize a typical torsion box box part between 20% and 85% span of a lifting surface (Fig. 9). Four sections will be analyzed: 20%, 40%, 60% and 85% of the span.

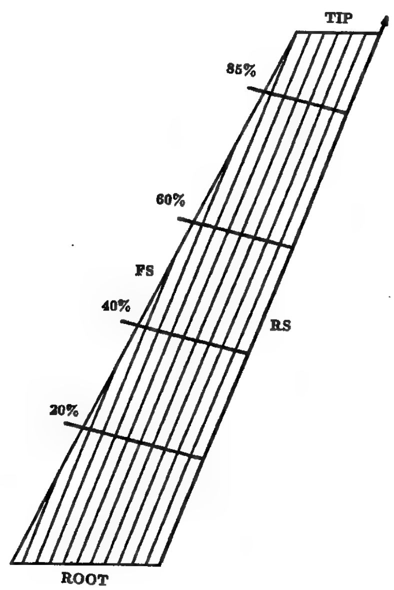


Fig. 9: Typical lifting surface torsion box

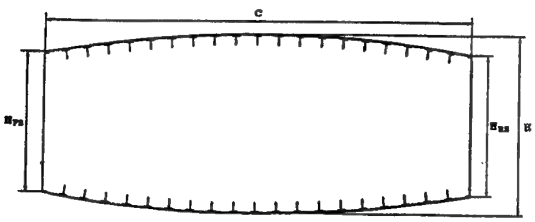
The analysis data are the following: (Units: N, mm)

- Materials:

  The stabilizer torsion box is made of composite materials, with the following laminate properties:

Property	Skins	Stringers
E_{xx}	53000	86000
E_{yy}	33000	29000
G_{xy}	21000	13000
μ	0.30	0.30

- Geometrical dimensions:



Section	C	H	H_{FS}	H_{RS}
	Parameters			
20% span	2100	700	675	600
85% span	1200	400	370	340

The ribs are spaced 700 mm, providing a clamping coefficient of 1.5 to support the stringers.

- Structural arrangements:

  - Number of stiffeners at 20% section: 12 at upper skin and 11 at lower skin.
  - Location: Equal spaced. Parallel to rear spar.
  - Stringers type: 1
  - Initial dimensions and variation ranges:

	Section at 20%			Section at 85%		
Param.	Init.	Min.	Max.	Init.	Min.	Max.
t_{st}	10	5	15	4	2	6
H_{st}	80	30	130	32	12	52
D_{st}	70	Fixed		30	Fixed	
t_{sk}	5	4	15	3	2	6
t_{sp}	8	4	15	4	2	8

- Loads:

Section	Case	Vertical Shear	Bending moment	Torque moment
20%	1	-850000	53000 x 10^5	13000 x 10^5
	2	650000	-38000 x 10^5	-3000 x 10^5
85%	1	-100000	2000 x 10^5	1000 x 10^5
	2	82000	-1000 x 10^5	500 x 10^5

(Referred to an axis located at 20% of the chord).

- Damage tolerance allowables:

  - Tens: 4000$\mu\varepsilon$; Comp: 3600$\mu\varepsilon$; Shear: 8000$\mu\gamma$

- Reserve factor:

  - Skin panels local buckling: 0.9.
  - Rest of analyses: 1.1

The results of the optimization process are summarized in the next table:
(CPU time 25' 20" in a VAX 7610)

Parameters		20%	40%	60%	85%
		Section			
t_{st}	Upper	11.4	9.6	9.4	2.6
	Lower	14.1	12.2	9.5	2.0
H_{st}	Upper	78.8	83.3	56.4	28.1
	Lower	87.1	86.1	82.0	38.5
D_{st}	Upper	70.0	57.7	45.4	30.0
	Lower	70.0	57.7	45.4	30.0
t_{sk}	Upper	10.0	10.2	9.4	3.6
	Lower	10.7	11.8	9.5	4.7
t_{sp}	Rear	7.4	6.8	4.9	2.0
	Front	4.8	4.4	2.9	2.0

In figure 10, the sections areas obtained in the different optimization steps are showed. In figure 11, the final sections areas are represented.

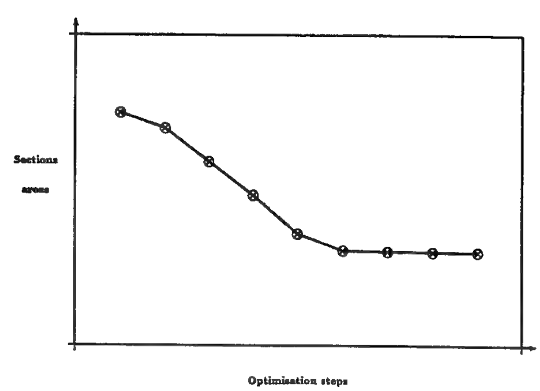


Fig. 10: Section areas along optimization steps

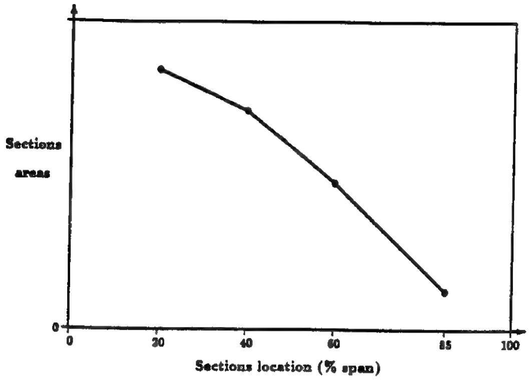


Fig. 11: Optimized section areas

11. APPLICATIONS

Program ALACA has been successfully applied in CASA to obtain the minimum weight of wings and horizontal tailplanes for the following airplanes:

MD-12X
CASA 3000
C255
A3XX
FLA

In all these cases a parametric study has been performed in order to obtain the optimum stringer pitch and rib spacing as it is shown in figure 12.

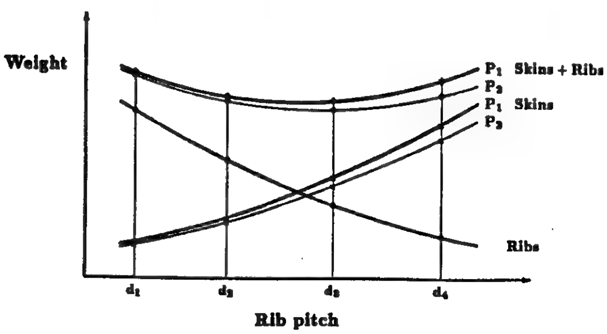


Fig. 12: Optimum arrangements selection.

12. CONCLUSIONS

- ALACA is an interdisciplinary design program combining stress and strength calculations, buckling, residual strength, manufacturing and aeroelastic constraints.

- This procedure will provide optimum skin and stringers distribution for composite or metal wings that satisfy strength, fatigue, damage tolerance, stability, manufacturing and flexibility constraints.

- The most important aspects are listed below:

  - Can be employed very effectively for studies in the trade off phase (metallic and composite constructions).
  - Simple structural model (not finite element models required).
  - High reliable strength analysis of torque box skins.
  - Powerful design tool.
  - High performance.
  - Good convergence.
  - Feasible stringers design.
  - Design for manufacturing requirements.
  - Accurately prediction of bending masses.

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HUMAN LIMITATIONS IN FLIGHT

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It seems obvious that, the major limitation for flight is, in humans, the lack of wings.

All we know that since the appearance of the human beings, around 1,6 millions years ago, their evolution is not so notorious as the technological evolution the same humans made on the devices they had built. The anatomical and physiological differences between the *Homo Habilis* and the *Homo Sapiens*, are less than the "anatomical" and "physiological" differences of the Wright Flyer when compared to a X-29.

Nowadays aircrafts can fly high, fast, during day and night,during all weather conditions, allowing humans to work during long periods, or in atmospheric layers to which they are not adapt.

The human senses, fundamental to life and survival are not well adapt to accelerations, vibrations, hypoxia and variations in pressure. But man had an answer to this challenges and created anti-G suits, masks to breath oxygen, pressurized cabins, night vision goggles, and a lot of other devices destinated to protect crewmembers from the aggre-ssions of fly.

Let us talk a little about the physiological problems: humans need oxygen to live, and this substance varies with altitude, due to the diminution of atmospheric pressure; it is only a question of partial pressures. Hypoxia, or lack of oxygen influences vision, celular metabolism, mainly brain metabolism, and if prolonged enough or in high level can produce incapacitation and death.

Vision is limited by distance, luminosity, and prone to illusions, mainly during night or under certain weather conditions. Eyes are also affected by vibrations, specially some ranges.

Ears, namely the inner ear are very sensitive to accelerations and noise. The last can produce deafness. Accelerations are one of the major sources of spatial illusions, these responsible for a

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lot of accidents, some of them leading to the death of pilots and other crewmembers.

Man lives with machines and both move in an environment, and this interactions can create problems, some of them of difficult resolution. We cannot change the environment, but we can train men and make machines suited for them. It is my personnal believe that, in our times, we make machines trying to achieve some parameters, forgeting very often that they are built for men.

In 1972, Prof. Edwards created a modular concept that tries to explain the relationships among men, machine and environment and, what is more important, also among men (the SHELL model where the letters have the following meaning: S - software - procedures, checklists, simbology,etc. H - hardware - cockpit layout, seating, controls, etc. E - environment - aircraft and airspace. LL - liveware - the crewmember and the interface between people, crew, operations staff, engineers, etc.)

This introduces the "psychological" side of our paper: judgement and decision making and information process.

Before this, it is necessary to correlate performance and state of arousal. The definition of the last is a person's preparedness for difficult tasks.there is an optimum level of arousal for a maximum of performance; any state of arousal under or above that optimum level,can lead to a bad performance, with all the risks that this can provoke on the flight safety.

The information process is very "easy" to explain: the information that is obtained by the senses is carried by neural pathways to the brain, where is integrated and processed. Then the brain makes a decision and takes an action. The memories (short term and long term have a main role during this process); the problems arrived when that information is incorrect or misinterpreted by the senses. It is very easy, in this case, the accident to occur. Information process can also be altered by expectancy, habits (usually bad habits) mental overworkload and stress.

The decision and action need judgement, i.e., a mental process by which human , in this case pilots, recognise, analyse and evaluate information about themselves, the aircraft and the operational environment in order to take the correct action.

Some problems that are human related can jeopardize the judgement and decision making, and in short this are: information transfer, language difficulties, misreading checklists, misinterpretation of instrument indications, incorrect operation of system controls (sometimes due to ergonomic errors), task saturation (frequent in modern aircrafts),

fatigue, bad habits acquired during training and professional life and psychological problems.

All this can lead to errors during flight, sometimes finishing in fatal accidents.

This brief and unpretensious exposition about something so complex, the human being, is necessarily incomplet and is only a tentative to show you, the "aircraft makers", that "flying humans" need all your comprehension to fly higher, faster, farther and **safer**.

Monte Carlo-based stochastic finite element method: A new approach for structural design

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ABBREVIATIONS

ASTM American Society for Testing and Materials
CDF cumulative distribution function
K-S Kolmogorov-Smirnov
L.E.V. Largest Extreme Value
PDF probability density function
S.E.V. Smallest Extreme Value
SFEM Stochastic Finite Element Method

Normal PDF:

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$$

Lognormal PDF:

$$f(x)=\frac{1}{\sigma x\sqrt{2\pi}}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right]$$

Weibull PDF:

$$f(x)=\frac{\eta}{\sigma}\left(\frac{x-\mu}{\sigma}\right)^{\eta-1}\exp\left[-\left(\frac{(x-\mu)}{\sigma}\right)^{\eta}\right]$$

Type I Smallest Extreme Value (SEV) PDF:

$$f(x)=\frac{1}{\eta}\exp\left[\left(\frac{x-\mu}{\eta}\right)-\exp\left(\frac{x-\mu}{\eta}\right)\right]$$

Type I Largest Extreme Value (LEV) PDF:

$$f(x)=\frac{1}{\eta}\exp\left[\left(-\frac{x-\mu}{\eta}\right)-\exp\left(-\frac{x-\mu}{\eta}\right)\right]$$

1. SUMMARY

The paper summarises the principles of the Monte Carlo based finite element method. The method relies on the characterisation, by means of stochastic tools, of the mechanical behaviour of different materials taking uncertainties into account. A procedure based on the combination of three methods for estimating distribution parameters has been set up to ensure correct estimation of the material properties that are used as input for the finite element model. The stochastic engineering design method is then applied to beam structures. Although the present report is limited to the linear analysis, it is concluded that attention should be paid to the Monte Carlo sample size required to obtain accurate results and to the appropriate choice of the finite element mesh to avoid excessive CPU time consumption and errors in the interpretation of the results.

2. INTRODUCTION

With the rapid development in the last decades of new materials such as composite materials, which are inherently more variable than metals, engineers are more and more confronted with structural problems in which uncertainties may play a crucial role. Lightweight structures exploiting the composite material capabilities, for instance their high specific modulus, as far as possible require appropriate design and manufacturing techniques. Since this requires a good knowledge of material properties and behaviour, there is an increasing need to achieve complete data acquisition and to quantify aspects of the material behaviour that can be modelled as random phenomena. Indeed, as mechanical properties of composite materials show greater variability than those of conventional structural materials, test data are required in a larger quantity and classical methods of deriving design data from test procedures cannot be used with sufficient confidence.

Other sources of uncertainties in design are the loading conditions of the structure. For example, environmental variables such as temperature and pressure are themselves random processes in time and space and stochastic dynamic loads are frequently encountered (noise,...). Appropriate design tools have to be developed to deal with these aspects.

Parallel to the characterisation of materials, modelling aspects are of great importance in the engineering field. When modelling is concerned and if variability could be rather large, it is usually advantageous to use probabilistic models rather than deterministic ones. An ideal random process model will capture the essential features of a complex random phenomenon with a minimum of parameters, which have to be experimentally accessible and physically meaningful.

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Whether or not formal treatment of uncertainty is warranted depends, among other things, on the quality and quantity of the information available, the importance of the problem and the resources at hand.

The finite element technique is a widely recognised modelling tool used in engineering, both for design and for analysis. With the rapid development of computers, this numerical technique is becoming a standard for engineers and designers, helping to reduce the costs during the design phase of engineering structures.

Hence, this research will give a brief insight into the method developed to generalise the use of stochastic description to any mechanical property, and more specifically for composite materials, used as input of the numerical model. The accent is put on the numerical modelling itself.

Monte Carlo techniques are used in combination with the finite element method to determine the stochastic distribution of the structural response on the basis of the stochastic description of the input (materials, geometry, loads, ...). Simple structures, such as a cantilever beam, to more complicated structures, like a composite perforated plate, may be investigated by means of the Monte Carlo-based finite element method. This analysis allows to establish the variations of the structural response related to variations in the input, as materials, geometry and loads. The advantage of this method is that it does not require access to the finite element source code and can be used, with some adaptations, to any code.

3. STATISTICAL CHARACTERISATION OF MATERIALS

3.1 Introduction

Advanced composite materials have properties which, viewed on an appropriate scale, exhibit complex pattern of variations in space and time. Composite materials are inherently more subject to uncertainties than "classical" materials such as metals. The manufacturing process itself is the primary cause of the material scatter, and can have unpredictable influence on composite materials behaviour and the nature of the composite itself.

Statistical characterisation of mechanical properties of composite materials is usually involved with ultimate properties, in statics or fatigue. Stochastic description of linear material properties as Young's modulus has only been considered from a theoretical point of view in numerical problems. Experimental determination of the stochastic character of material elastic properties is nonetheless a point of paramount importance for a probabilistic approach to reliability of complex structures. As a matter of fact, the stochastic aspect of stress is related to the stochastic behaviour of material properties, including the elastic properties, geometry and loading conditions.

Tensile stress/strain curve for the carbon/epoxy composite are determined by means of destructive tensile tests on specimens following the ASTM standards (D3039M). The various steps in the manufacturing and testing process are performed with an accuracy as high as possible, to reduce to a minimum the dispersion of the results obtained. This procedure then gives an indication of the minimum dispersion that could be obtained with materials of good quality, correctly calibrated equipment and skilled operator. If the tests conditions are not so favourable, e.g. in an industrial context where the process control may be difficult, or when working with lower quality materials, a higher dispersion of the results should be expected. The important point is that the specimens that are used to perform the material characterisation have similar properties to the material used in the real structure to be analysed. For composite materials, this implies that the material has to be manufactured in the same conditions for the test specimen and the structure: same manufacturing technique, equivalent environmental conditions,...

Another type of departure from the ideal case occurs when the material properties are not homogeneous within the structure. For composite materials, the manufacturing technique itself induces non homogeneity: fibre- and resin-rich regions at different points of the structure, whether it is pultrusion, hand lay-up, ... When this problem arises, one should think carefully of what type of specimens to use for the characterisation: standard test specimens are probably not the most indicated choice, and it could be more meaningful to realise test specimens reflecting the real conditions.

3.2 Choice of a distribution

The first question that arises is which distribution would best fit the data obtained? Is it possible to choose the model on the basis of physical evidence? Or can any experiment with classical materials be of any use for composite materials? Or is the empirical approach the last resort solution? A literature review shows that some distributions are regularly used, such as the Weibull, lognormal, normal and extreme values, to characterise material strength, not always on physical evidence, mainly by comparison with similar investigations on similar materials.

The choice of a distribution to fit experimental data should best be performed by understanding the underlying phenomenon. This requires a more detailed investigation, which is not performed here. A short review of the physical mechanisms linked to the definition of material properties, and more specifically composite materials, is presented in VAN VINCKENROY, 1995.

As experimental data are available, a way of choosing the distribution consists in graphically fitting the data. This can be achieved by approximation of the sample

relative frequency, graphically represented by the data histogram, or the hazard function. The choice based on the hazard function is a typical approach in reliability.

The sample relative frequency as well as the sample hazard function give a first insight into the distribution that can be chosen. Symmetrical histogram suggests that a distribution such as the Normal distribution should be used for the theoretical probability function. Left skewed histogram suggests that a distribution such as the Smallest Extreme Value distribution or Weibull distribution (with shape parameter greater than unity) should be used. Right skewed histogram would suggest the use of Largest Extreme Value, Lognormal or Gamma (with shape parameter greater than unity) distributions. Exponential type histograms would be best fitted by Gamma or Weibull distributions (with shape parameter smaller or equal to unity).

The hazard function, expressing the probability that the event under consideration occurs during a very small increment of the variable, given that it did not occur previously, is widely used in reliability as the rate of failure, when the density function under consideration is characterising failure. Each hazard function has a unique corresponding PDF, in such a way that the PDF best fitting the data can be uniquely determined. A exponentially increasing hazard function would suggest the use of a Weibull (with shape parameter greater than unity) or Smallest Extreme Value distribution. A slowly increasing hazard function is characteristic of a Normal distribution. A horizontal asymptotically increasing hazard function would suggest the use of a Largest Extreme Value, Gamma or Lognormal distribution. A decreasing hazard function is characteristic of Gamma or Weibull distributions (with shape parameter smaller or equal to unity).

When plotting histograms, it can happen that some categories are empty due to the presence of outliers at the extremes. Tests have to be performed to know if the outlier may be rejected before constructing the fitted distribution (DALLY, 1979; ROUSSEEUW et al., 1987). Once the outliers are extracted, the mean and standard deviation of the "corrected" sample are calculated as well as the histogram and hazard rate.

3.3 Parameters estimation and goodness-of-fit tests

Once the type of distribution has been chosen, based on the histogram and hazard rate, estimates of the model parameters are calculated by probability plotting, maximum likelihood method and moments method. When the choice could not be performed uniquely, the determination of the goodness-of-fit for the various distributions under consideration will help selecting the distribution that best fits the data.

The three parameter estimation methods are used in order to analyse the possible influence of the method chosen on the type of distribution to be selected, the values of the parameters and the goodness-of-fit. All three methods are indeed relying on different characteristics of the probability function and approaches to determine the best choice. Each method has its own advantages and drawbacks, depending also on which type of distribution is has to be applied. As an illustration of this, the maximum likelihood method can be considered: the determination of the parameters of the selected distribution is performed on the assumption that the sample represents the most likely value of the variable under consideration. The values of the parameters, denoted as the maximum likelihood estimates, are usually the best estimates. They are easily determined in the case of a Normal distribution, but the determination of the parameters of a Weibull or Extreme Value distribution requires the solving of non linear equations, which is a quite complicated subject due to the complex shape of the functions to be numerically solved. The benefit of the quality on the parameters estimation may be lost by the approximations in the numerical solution. Considering the probability plotting, this graphic method is quite versatile, and the parameters of any distribution are easily determined, but the drawback of it is that the quality of the estimation is poor.

The use of the three methods in parallel or in combination is investigated in order to establish an adequate procedure for the determination of best fit distributions for experimental material properties.

An important topic that has to be considered simultaneously with the parameters estimation is the goodness-of-fit. Once the parameters have been calculated, statistical tests are performed to evaluate how good is the fit and what is the confidence on the parameters values. This step is of paramount importance as the distribution selected and the parameters calculated are unusable as long as there is no proof that the choice made is the correct one among various possibilities.

The statistical tests performed to determine whether the chosen distribution provides an adequate fit to the data are the following: the regression analysis and the Kolmogorov-Smirnov test.

Errors estimates on the parameters are calculated by determining the standard deviation of the parameters. It is usually possible to estimate the standard deviation of the parameters, provided that an explicit expression of the parameters in function of the data does exist. For parameters derived by numerical solution of non linear systems, approximations may be used, or results may be found in literature.

The various parameters estimation methods, goodness-of-fit and errors estimates determination tests were implemented in a C program on SPARCworkstations. Table 1 illustrates in detail the method applied to the longitudinal Young modulus for an aluminium alloy, namely Al2024-T3, used as reference material in this investigation. Detailed results for composite materials can be found in (VAN VINCKENROY, 1995).

3.4 Conclusion

At the end of the experimental section, different important conclusions can be drawn. The first is that a complete stochastic characterisation of material properties of some materials has been performed. Not only strength, which is usually considered in literature, is investigated but also linear properties, like Young modulus and Poisson coefficient. Those are generally not considered for stochastic characterisation in literature, except eventually from a theoretical point of view, but not experimental.

This stochastic characterisation relies on a procedure including various steps: choice of a distribution on an empirical fit unless the phenomenon is perfectly understood in such a way that an analytical basis allows to choose the distribution with similar properties. Nonetheless, actual knowledge of the mechanisms in composite material does not permit the latter type of choice. The empirical fit is based on the relative frequency and hazard rate of the sample. Finally, estimation of the parameter values and goodness-of-fit assess the choice quantitatively.

All three methods, i.e. probability plotting, method of moments and maximum likelihood method, are used in parallel. The probability plotting has the advantage of being versatile: the parameters, the error estimates and the goodness-of-fit can be calculated for any type of distribution; its drawback is that it is sometimes quite inaccurate: a parameter value estimated by probability plotting can be as far as 20% greater than the same parameter estimated by the other methods. The error estimate can be greater with this method than with the others. The results from the probability plotting method are used as start values in the case of non-linear system in the maximum likelihood method and the method of moments. Both these methods are usually more accurate, but when dealing with non-linear systems, not always converging to a solution.

There is usually a good agreement between the results of the three estimation methods. Some disagreement or a small goodness-of-fit result are generally the consequence of a too small sample size. In a general way, the sample size has to be large enough in order to obtain a good fit, with a high degree of confidence and small error estimates. When a distribution is fitted to the data, the largest deviations between observed values and distribution occur at the extremes, in the tails of the distribution. These errors can be reduced by increasing the sample size. The minimum sample size needed to attain a given level of confidence depends on the nature of the data.

At that point, the properties have been characterised statistically, and they are used further on as input for the numerical model. The numerical aspects are described in next paragraph.

4. SFEM ANALYSIS

4.1 Introduction

It is common practice in engineering to use safety coefficients in combination with deterministic design or analysis, to cover the uncertainties that characterise real structures, and to increase confidence. The various types of uncertainties that are encountered are the following:

- the *inherent variability*, due to variations in material properties and geometry of the structure, and environmental uncertainties (temperature, loads, boundary conditions changes)
- uncertainties due to *measurement errors* (limitations of test benches and human error), when experimentally characterising the material
- *model imperfections* when models are used, as for numerical techniques (non perfect modelling of boundary conditions, approximation in the element choice to model physical behaviour, approximation in loads modelling, ...)

It is widely recognised that the above effects can have a drastic influence on the structural response. The need for adequate tools taking these stochastic aspects into account is obvious, and the growing interest for stochastic numerical tools is becoming gradually evident.

Uncertainty has focused the attention of researchers at the beginning of the seventies: SHINOZUKA (1972) investigated the digitalisation of random fields to be used in Monte Carlo simulation. Analytical models have been proposed, as by SHINOZUKA and his associates (SHINOZUKA, 1987; BUCHER et al., 1988 and KARDARA et al., 1989) for simple linear elastic structures. However, the present research is focused on developing numerical tools to deal with stochasticity.

The *finite element method* is a powerful numerical tool in the solution of all kinds of problems locally described by partial differential equations. The method is based on the discretization of the structure in sub-domains (finite elements), within which the required quantities (displacements in the case of potential energy-based approach) are expressed by polynomial approximation, reducing the solution of the variational problem to the solution of an algebraic equation system. This technique is especially necessary for complex problems, for which no analytical solution can (easily) be found. In particular, it is widely used in engineering problems, where the structures can be quite complex: geometry, non linearities, time dependence, etc. But many applications in engineering require also representation of uncertainties. So the introduction of the stochastic method is natural: its aim is to facilitate the modelling of stochastic aspects into structural analysis.

4.2 The Monte Carlo-based SFEM

The method developed in this paper relies on Monte-Carlo simulation of random fields and variables discretized to be used in conjunction with the finite element method. The objective is to relate the stochastic character of the input of a complex composite structure to the stochastic character of material properties, structure geometry and loading conditions. The method will be developed with emphasis on linear elastic statics or dynamics of composite structures. Non linearities, material as well as geometric, will not be considered here, and will be the subject of a future extension of the current paper. Reliability, related to non linear behaviour of material and structures and ultimate properties will therefore not be considered neither.

Principles, advantages and drawbacks of the method, with their possible bypasses will be reviewed. The various steps in the development of the method are then analysed. And last but not least, possible extensions will be briefly exposed.

4.2.1 Motivations, advantages and drawbacks

It has been seen in the literature review that most common stochastic finite element techniques can be classified into two categories: the methods using perturbation techniques, relying on a Taylor development of first or second order of the stiffness matrix, and the methods relying on Monte Carlo approach not requiring the knowledge of the stiffness matrix. If actual finite element codes are considered, no commercial finite element code integrating stochastic aspects of input. can be found on the market. If one wants to introduce those aspects into the code by means of the perturbation techniques, one will need access to the code. This is usually not feasible for two reasons, developed below.

The first reason is that unless the code is home-developed, the user is usually not allowed to access the source code of any general finite element program. Secondly, even when the source code is available, it is generally tedious work for an outside user to suitably modify the code in order to introduce these stochastic aspects. This means that if a finite element program has to be modified in order to incorporate stochastic approach by means of the perturbation technique, very few people are able to perform this task.

The first advantage of the method developed in this paper is precisely its versatility: any finite element program can be used as framework of the SFEM, some small routines have to be adapted in order to deal with differences of input and output data of the finite element program selected.

The second advantage of considering Monte Carlo technique, although this is not yet considered in this work, is that non-linearities could be considered, whereas the perturbation technique is only applicable for small variations; moreover, it has been shown to be relatively inaccurate in dynamics. Nonetheless, Neumann expansion enables to consider larger variations.

One drawback associated to the use of Monte Carlo techniques is that they are CPU consuming. However, with current computer developments, this is no longer a major drawback although this fact has to be borne in mind if there is some quotas on memory and disk space assigned to the problem.

4.2.2 Principles

Materials properties, such as the Young modulus, the Poisson coefficient or density are supposed to present some stochastic variations. Ultimate properties do also vary statistically, but they are not considered here since only elastic cases are analysed, thus no structure is considered for failure. Geometric variables may also be submitted to random fluctuations, e.g. plate thickness, corners shape, beam length,.... Randomness in load may also be considered.

Once the deterministic finite element model has been set up for the structure under consideration, the stochastic aspects are introduced in the model. The materials properties and/or the loads and/or some geometric variables are supposed to follow a given statistical distribution, and not to have a defined value. Given the distribution functions, that is, their type and values of parameters, a random generator program is used to generate deviates from those distributions. The random values of the stochastic properties are then introduced in the model. The structural response is thereafter determined for this configuration of material properties, geometry and loading conditions, by means of FEM. The structural response may be the maximum stress, maximum strain, or any state variable.

The Monte Carlo simulation consists now in assigning other random values, determine the state variable and repeat the procedure in order to obtain sufficient data to build up the statistical distribution of the state variable. The procedure is illustrated by the flow chart in (VAN VINCKENROY et al., 1992)

4.2.3 Random field discretization

The finite element method requires all fields to be discretized: the structure is divided into elements to which material properties are assigned, the load density is represented by nodal forces,.... When deterministic problems are considered, values are assigned to each element in a well defined manner. For isotropic materials, the same value is assigned to all elements; for layered composite structures, the material properties are assigned to the elements layer by layer; the load density is uniquely defined and known in each point; etc.... When the stochastic character of all these variables is considered, those are assumed to vary randomly in space

and thus the value assigned to the elements or nodes will vary from element to element and from node to node, also on a random basis.

In this stochastic approach, materials properties, geometric variables and loads are supposed to be modelled by homogeneous random fields: in each point of the space, the property follows the same density function. Composite materials are generally considered as homogeneous on macroscopical scale, according to the mechanics of composite materials. Random numbers are extracted from the same density function and assigned to the different elements under consideration. The question that arises is to know if there is some correlation between the variable value at a point and its value in another point.

In a first instance, materials properties are assumed to be modelled by a purely random field, for which the correlation function is a delta function. In other words, the value in one element is independent from the values in the other elements. The physical significance of this is that material properties in each point are independent of the values of the properties in the surrounding points. An extreme case that results from this assumption is that neighbour elements can exhibit very different values, simulating a high gradient of the property of concern. High gradients in material properties are not likely to occur in a homogeneous medium, except in the presence of defaults, defects, cracks or flaws. Composite materials, due to their nature and the manufacturing techniques are more susceptible to contain defects than metals. On the other hand, the random values are generated from unimodal, non uniform distributions, which means that the occurrence of highly different values is not so probable.

The conclusion of this is that the assumption of non correlation is not so unrealistic, and that it is on the side of safety, modelling extreme cases.

This assumption represents also the simplest case to simulate: random numbers from the given distribution are generated directly by means of a random number generator, without any other treatment. These random numbers are mutually independent by essence, thus non correlated. Each random number is then assigned to one element in the mesh. Generation of property values that are correlated in each point of the space is quite straightforward, provided a correlation function is known. And there is the main difficulty: experimental determination of this correlation function is not easy, theoretical correlation functions are usually found in references, as shown in previous review.

The structure is divided into finite elements small enough to consider the material property constant in each element. In that way, each element is assigned a value generated from the given distribution. There is no separate random field mesh, the finite element mesh is used for the discretization of the random field.

In the method developed here, we use the univariate probability density function as experimentally described in previous paragraph, to model the random fields for 1-dimensional or 2-dimensional problems, as the condition of homogeneity implies that the random fields expression does not depend on the absolute location.

On the level of numerical considerations, two points need some developments: the type of random numbers generator to be used and the importance of the Monte Carlo sample size.

4.2.4 Random numbers generation

Some important considerations about random numbers generators will be briefly discussed here, as some problems were encountered when porting the code from one workstation to another. There is a built-in random generator in most C libraries, which is usually a linear congruential generator. One has to be really suspicious about the randomness of numbers generated through such generators, due to their low randomness in the random sequences. Several improvements of the randomness can be achieved by using *shuffling* procedures, introducing random permutations into the random sequence. Another point which is of interest is to build a portable random number generator, which will generate the same random sequence on all machines. Portable generators have the disadvantage of running more slowly, but the advantage of being architecture-free, with an infinite period and without sensible sequential correlations.

In this work, random numbers have to be sampled from non uniform distributions representing the stochastic character of the finite element input data. This is performed by applying a transformation between uniform density function and CDF of any statistical variable, says $F(\underline{r})$. Indeed, any CDF is a uniformly distributed variable on [0,1] and then, to get a value x of a random variable X, get a value r of a random variable $\underline{r}$, compute $F^{-1}(\underline{r})$ and set it equal to x.

4.2.5 Monte Carlo sample size

An important topic in Monte Carlo simulation is the size of the sample, that is, the numbers of observed random variables in the sample. The Monte Carlo-based SFEM is concerned with the determination of the probability function of a state variable, thus with the determination of its parameters. It can be shown that the error on the parameters estimates are inversely proportional to the sample size (VAN VINCKENROY, 1995). Unless variance reducing techniques are applied, a reduction of variance is obtained by an increase of the sample size.

In this work, variance is reduced by increasing the number of simulations, thus increasing the sample size for the variable to be analysed. From the variance of the parameters, convergence can be checked against the

number of simulations necessary to obtain a given level of confidence on the parameters values, whatever the estimation method and goodness of fit test may give.

4.2.6 Conclusion

This paragraph is the central key of the method developed in this paper. After a review of literature concerning finite element method combined to stochastic approach, it appears that most work in this area is based on the perturbation approach. The Monte Carlo-based SFEM presented here is an alternative to these techniques. Its versatility relies on the introduction of the stochastic aspects from outside the source code, and on the fact that it is not limited to small perturbations.

Some points requiring special attention have been developed: the correlation effect, the quality of the random number generator and last but not least, the effects of sample size on the results.

5 APPLICATION: The Cantilever beam

5.1 Deterministic analysis

To illustrate the method applied, let us consider a cantilever beam submitted to a concentrated load at the free end. In a first instance, we consider only stochastic material properties, and the geometry and the load are deterministically defined: length of one meter and load of 1000 N. The section has a moment of inertia with respect to the z-axis of 1.66829e-06 m^4. The structure is illustrated at Figure 2.

A deterministic analysis is performed with following values, typical for aluminium:

Young modulus: 72.16 GPa
Poisson coefficient: 0.33

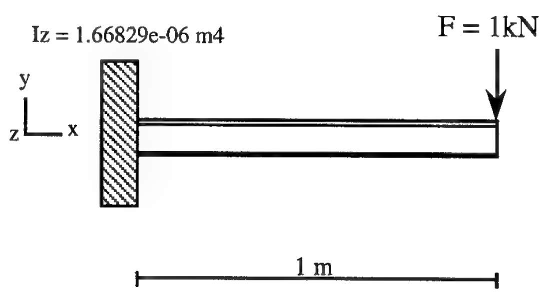


Figure 2- Cantilever beam submitted to a concentrated force.

The variable of interest is the maximum deflection (at the free end). This problem can be solved analytically and the maximum deflection obtained at the free extremity of the beam is given by:

$$y_{max} = \frac{Fl^3}{3EI_z} \tag{1}$$

where I_z is the moment of inertia of the section with respect to the horizontal axis,
E is the Young modulus of material
F is the applied force
l is the length of the beam.

In the present model, the maximum deflection is equal to 2.769mm.

The finite element model is now considered. The beam element used in the model is a displacement formulated first degree (linear) beam without transverse shear deformation. For the deterministic analysis, the maximum deflection is independent of the total number of elements in the model, and is equal to 2.769 mm.

5.2 Stochastic analysis.

For the stochastic analysis, materials properties are supposed to be described by univariate homogeneous spatial fields: the distribution is the same in each point and random values are thus extracted from one and unique distribution; each random value is assigned to one element of the finite element mesh. In this first study, the correlation function of the material property is supposed to be a delta function, which means that the value in one location is independent from the values in the neighbourhood.

The Young modulus is assumed to follow a Weibull distribution, based on experimental data. To check the influence of the distribution type, Normal and Lognormal distribution are also used, although the experimental results show that the goodness-of-fit test for these distributions is poorer in the case of aluminium. The experimental Al2024 distributions are given in Table 1.

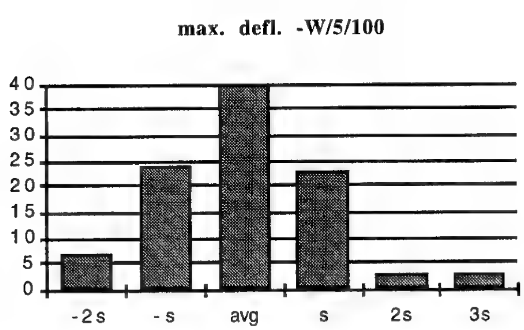
The Poisson coefficient does not have any influence on the maximum deflection of the beam. Therefore, the value used in the deterministic analysis is also used here.

Random numbers from the chosen distribution are generated by the technique described in previous paragraph. Each value is assigned to an element of the finite element mesh and the finite element analysis is then performed, yielding one value of the maximum deflection. Repeating these steps several times, for various random numbers and summarising the output data by means of the same procedure as for the experiments, yields the distribution function of the maximum deflection.

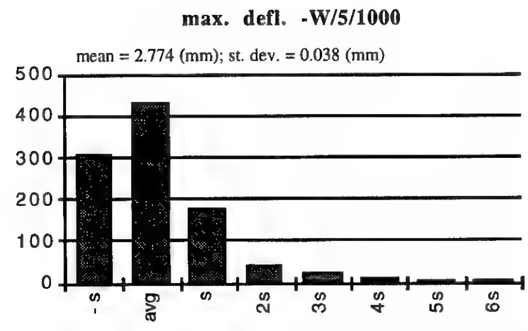
The influence of various factors is investigated:

- **the Monte Carlo sample size.**
  The number of simulations performed is an important factor influencing the accuracy of the parameters of the distribution fitted to the sample data. If the number of simulation is too low, or in other words if the resulting Monte Carlo sample size is too small, the parameters are not determined with a high degree of confidence. The error estimates are large and the type of distribution that best fits the data could also be different for different sample sizes. To investigate this effect, determination of the maximum deflection distribution is performed for an increasing sample size. Four cases are investigated: 100, 500, 1000, 2000 simulations. For each case, a complete procedure similar to the one used for the characterisation of experimental material properties is followed in order to determine the best fitting distribution, its parameters and the error estimate on the latter. Table 2 reports the average and standard deviation of the sample, together with the type of distribution that best fits the data, with 90% confidence, its parameters and the corresponding error estimate. The finite element model used in this case includes 5 elements and a Young modulus described by a Weibull distribution (see Table 1).

It can be seen from this table that when the sample size is too small (100 observations), there is no best fitting distribution, the goodness-of-fit test fails to reject more than one distribution instead. Moreover, the error estimate on the parameters are larger than in the case of a higher number of simulations. The minimum number of simulations needed to attain convergence and to determine uniquely the best fitting distribution is equal to 500 in this case, and depends generally on the problem. It has to be noted that when convergence is reached, all three estimation methods give parameter values that are the same to within the error estimate.



(a)



(b)

Figure 3 - Histogram for the maximum deflection for (a) 100 simulations and for (b) 1000 simulations

The figures 3a and 3b represent the histogram of the maximum deflection in the case of 100 and 1000 simulations respectively. It illustrates clearly the effect of increasing the sample size. The average and the standard deviation do not vary significantly, but the form of the distribution changes: the greater the number of simulations, the greater the accuracy of the tails.

- **the mesh.**
  The influence of the random mesh on the stochastic behaviour of the structural response is investigated next. Monte Carlo simulation is applied to finite element models with element numbers varying from 5 to 100. 1000 simulations are performed for each model. For these simulations, the Young modulus is assumed to follow a Weibull distribution (see Table 1).
  The average and standard deviation of the maximum deflection sample, as well as the characteristics of the best fitting distribution are given in Table 3.

A consequence of increasing the number of elements in the model is a decrease of the standard deviation of the resulting maximum deflection sample, the mean remaining the same. The evolution of the standard deviation with the number of elements is illustrated in Figure 4. This has to be compared to the analytical expression for the variance computed from Equation (1):

$$s_y = y\frac{s_E}{E} \tag{2}$$

where s_y is the standard deviation of the maximum deflection y, and s_E is the standard deviation of the Young modulus E.

The value of the standard deviation in this case is equal to 0.0487: it represents the upper limit of the curve in Figure 4, when the model includes one element.

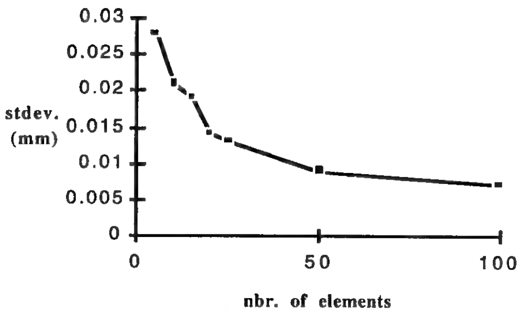
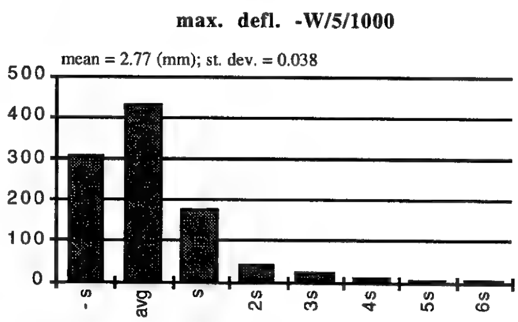


Figure 4 - Evolution of the standard deviation for the maximum deflection sample with the number of elements in the beam model.

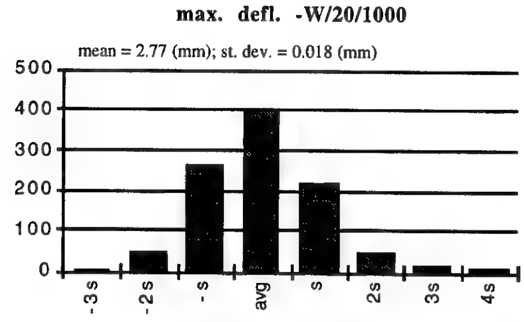
Using a finite element model with up to 10 elements and when the Young modulus follows a Weibull distribution, the deflection at the free end of the Cantilever beam has a PDF skewed to the right as seen from its histogram (Figure 5a). Statistical treatment of the data yields the best fitting distribution as being the LEV distribution.

However, refining the mesh gives as result that the K-S goodness-of-fit for the LEV distribution decreases drastically while the regression test now also fails to reject both the Normal and Lognormal distributions. The histogram becoming more symmetric (Figure 5b), it can indeed be fitted by various types of distributions, including the Normal, Lognormal and Extreme Value distributions, with appropriate parameters. Considering the LEV distribution, the parameter μ, related to the average, does not change significantly, but the parameter σ, related to the standard deviation and the distribution shape decreases significantly when the number of elements increases, down to 50%.

On the other hand, the lack of fit for all distributions displayed by the K-S test could be an indication of its limitations. Further analysis should be performed to quantify the validity of the K-S test, as it is known that its accuracy is reduced in the distribution tails. This subject will not be treated in this paper.



(a)



(b)

Figure 5 - Histogram for the maximum deflection of the cantilever beam with (a) 5 elements and (b) 20 elements

The evolution of the maximum deflection distribution, i.e. the decrease of the scatter reflected by the decreasing standard deviation, and the decrease of the skewness leading towards a symmetric distribution, can be explained by averaging and variance reducing effects. An increase of the number of elements with material property constant within one element but varying randomly from one element to the other, induces a diminution of the relative scatter, thus the standard deviation, of this material property on the whole structure, which in turns induces a diminution of the standard deviation of structural response. And following the central limit theorem, a variable resulting from an addition of random variables, whatever their distribution, tends to be Normal.

- **the type of distribution.**
  The influence of the type of distribution chosen to characterise the material properties on the distribution of the structural response is investigated in this section and the following one. Three different types of distribution are applied to the Young modulus, these distributions having the same average and standard deviation as the previous Weibull distribution. The structure is modelled with 10 elements and 1000 simulations are performed. For each case, the maximum deflection average and standard deviation are given in Table 4 together with the characteristics of the best fitting distribution.

When the Young modulus has a low standard deviation, the type of distribution used to model it does not influence the maximum deflection distribution. This conclusion is no more valid when the dispersion of the material properties increases as shown below.

- **the dispersion of the material properties.**
  To further analyse the influence of the type of distribution describing the material properties on the stochastic character of the structural response, material property displaying a greater scatter is introduced into the model. Random numbers are generated from a material property distribution with the same average as the one in previous paragraph,

but with a standard deviation ten times greater. The results for a Young modulus normal distribution are shown in Table 5.

When the standard deviation of the Young modulus increases, the various goodness-of-fit tests give similar results: only the LEV distribution fits the maximum deflection data. The average increases and the standard deviation even more, proportionally to the material standard deviation.

If the Young modulus is described by another distribution, i.e. the Lognormal of the previous paragraph, with identical mean but larger standard deviation (x10), the resulting distribution of the maximum deflection changes from LEV (see previous section) to Lognormal, as indicated in Table 6.

Following conclusion can be drawn: the distribution of the displacement of the free end of the cantilever beam follows a LEV distribution whatever the distribution for the Young modulus may be, provided that the standard deviation of the latter is small, i.e. about 2%. Nonetheless, when the dispersion of the Young modulus is larger, there is a change in the best fitting distribution, although its right-tailed shape remains.

Remark:

It has to be noted that during the random number generation, if the distribution of the material properties is not limited to positive values (left bonded), as in the Largest Extreme Value distribution, negative numbers could be generated. These numbers, although mathematically possible, do not have any physical significance and have to be rejected before introduction into the finite element model. This manipulation, consisting in truncating the distribution tail introduces a small bias, but as this bias remains relatively small (1 for 100, 4 for 1000, 27 for 10000), it could be neglected. The question arises in which measure is it valid to use non left bonded distribution to fit the material properties experimental data, that are always positive!

5.3 Conclusions

The simple example of the cantilever beam illustrates clearly which are the factors influencing the stochastic behaviour of the structural response, in the case of random fields or random variables. The Monte Carlo sample size is one of the most important factors, and the choice of the number of simulations should be carefully analysed to check for convergence of the fitting procedure. When random fields are considered, the mesh has also a non negligible influence, and one has to choose carefully the number of elements needed to represent adequately the discretize the random field.

The method has also been applied successfully to composite materials and structures, e.g. perforated plate in carbon/epoxy composite material (VAN VINCKENROY, 1995).

6 GENERAL CONCLUSION AND FURTHER RESEARCH

The main purpose of this work was to develop the first step, i.e. linear analysis, in an alternative approach to account for uncertainties encountered during design, construction and lifetime of structures, based on the use of statistical tools in material characterisation and structural design by means of the finite element method, combined with Monte Carlo techniques.

This work contributes to the characterisation of the mechanical behaviour of different materials, among which composite materials, by means of stochastic tools, taking all uncertainties into account. The method is applicable to linear elastic properties as well as strength of aluminium, adhesive and carbon/epoxy composite (VAN VINCKENROY, 1995).

The choice of the type of distribution is made empirically or on basis of the understanding of the phenomenon which causes the uncertainty.

All three methods for parameters estimation should be used to ensure correct estimation: linear regression can yield a first estimate when non linear systems are involved in the maximum likelihood method and the method of moments, while the last two methods yield more precise results. With actual computer capabilities, the calculations involved should not be considered as a penalty.

In this work, the influence of stochastic variations of the input parameters on the structural response of simple structures has been investigated and quantified. Furthermore, some considerations about the procedure should be emphasised: attention should be paid to the Monte Carlo sample size required to obtain accurate results and to the appropriate choice of the finite element mesh to avoid unnecessary calculations that could lead to errors in interpretation of the results.

This work is a first attempt to introduce Monte Carlo based stochastic tools in engineering design for composite structures. Therefore, it has been limited to the linear analysis. A quite logical further development of the method will be to take into account non linearities (in geometry, material or loading conditions) for non deterministic analysis. In this case, the stochastic treatment should be included in the source code of the finite element program to improve efficiency.

Another interesting point would be the incorporation of correlated variables or fields into the Monte Carlo based stochastic finite element method, with physical meaning to explain the correlation.

And last but not least, reliability should be incorporated in order to develop the so-called reliability finite element method (RFEM).

7. ACKNOWLEDGEMENTS

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9. TABLES

Parameter estimation technique: probability plotting

	Normal	Lognormal	Weibull	Smallest E.V.	Largest E.V
parameter 1	$\mu = 72.1425$	$\mu = 4.2784$	$\eta = 58.8985$	$\mu = 72.7829$	$\mu = 71.4686$
parameter 2	$\sigma = 1.5563$	$\sigma = 0.0217$	$\sigma = 72.7797$	$\eta = 1.2159$	$\eta = 1.3342$
correlation (r-squared)	0.8997	0.8963	**0.9619**	**0.9630**	0.7999

Parameter estimation technique: method of moments

	Normal	Lognormal	Weibull	Smallest E.V.	Largest E.V
parameter 1	$\mu = 72.1562$	$\mu = 4.2786$	$\eta = 74.5292$	$\mu = 72.7097$	$\mu = 71.6026$
parameter 2	$\sigma = 1.2298$	$\sigma = 0.0170$	$\sigma = 72.7065$	$\eta = 0.9588$	$\eta = 0.9588$
KS test:					
dmax	0.1715	0.1748	**0.1215**	**0.1237**	0.2417
probability	0.7342	0.7121	**0.9721**	**0.9670**	0.3070

Parameter estimation technique: Maximum likelihood method

	Normal	Lognormal	Weibull	Smallest E.V.	Largest E.V
parameter 1	$\mu = 72.1562$	$\mu = 4.2786$	$\eta = 80.3811$	$\mu = 72.7274$	$\mu = 71.5030$
parameter 2	$\sigma = 1.2298$	$\sigma = 0.0171$	$\sigma = 72.7093$	$\eta = 0.8651$	$\eta = 1.3278$
KS test:					
dmax	0.1715	0.1745	**0.1329**	**0.1346**	0.2027
probability	0.7342	0.7142	**0.9400**	**0.9339**	0.5266

Table 1 - Distribution for Young modulus for the AL2024-T3 derived from experimental data

nb of simulations	deflection average	deflection standard dev.	type of distribution	parameter 1 (st. dev. 1)	parameter 2 (st. dev. 2)
100	2.776	0.035	LEV/ (Normal/ Lognormal)	μ=2.7599 (0.0039)(*)	η=0.0294 (0.003)(*)
500	2.771	0.037	LEV	μ=2.7543 (0.0018)	η=0.0292 (0.0013)
1000	2.774	0.038	LEV	μ=2.7564 (0.0013)	η=0.0297 (0.0009)
2000	2.774	0.037	LEV	μ=2.7566 (0.0009)	η=0.0295 (0.0007)

Table 2 - Results of Monte Carlo simulations for the Cantilever beam deflection. Influence of the sample size, Young modulus following Weibull distribution

(*)The goodness-of-fit tests fail to reject the LEV distribution and the Normal and Lognormal distributions as well .

nb elements	deflection average (mm)	deflection standard dev. (mm)	type of distribution	parameter 1 (st. dev. 1)	parameter 2 (st. dev. 2)
5	2.7735	0.0381	LEV	μ=2.7564 (0.0013)	η=0.0297 (0.0009)
10	2.7739	0.0260	LEV	μ=2.762	η=0.021
15	2.7737	0.0220	LEV(*)	μ=2.764	η=0.019
20	2.7732	0.0182	LEV(*)	μ=2.765	η=0.014
25	2.7735	0.0175	LEV(*)	μ=2.766	η=0.013
50	2.7731	0.0118	LEV(*)	μ=2.768	η=0.009
100	2.7733	0.0084	LEV(*)	μ=2.769	η=0.007

Table 3 - Results of Monte Carlo simulations (1000 simulations) for the Cantilever beam deflection. Influence of the mesh, Young modulus following Weibull distribution

(*) The goodness-of-fit test based on probability plotting fails to reject the hypothesis of LEV, Lognormal and Normal distributions as well. Simultaneously, the other tests yield poorer fit for the LEV than with the models with less elements, and the goodness-of-fit test for the other types of distributions remains poor.

E distribution type	deflection average (mm)	deflection standard dev. (mm)	type of distribution	parameter 1	parameter 2
Normal	2.772	0.027	LEV	2.759	0.023
Weibull	2.774	0.026	LEV	2.762	0.021
Lognormal	2.771	0.028	LEV	2.758	0.024

Table 4 - Influence of Young modulus distribution on the maximum deflection distribution. (equal average and standard deviation)

E standard deviation	deflection average	deflection standard dev.	type of distribution	parameter 1	parameter 2
x1	2.772	0.027	LEV	2.759	0.023
x10	2.932	0.343	LEV	2.779	0.267

Table 5 - Results of Monte Carlo simulation for the Cantilever beam deflection, with Young modulus (normal distribution) standard deviation multiplied by 10.

E distribution type	deflection average	deflection standard dev.	type of distribution	parameter 1	parameter 2
Normal	2.932	0.343	LEV	2.779	0.267
Lognormal	2.910	0.291	Lognormal	1.063	0.098

Table 6 - Results of Monte Carlo simulation for the Cantilever beam deflection, with Young modulus standard deviation multiplied by 10.

THE GAS TURBINE ENGINE CONCEPTUAL DESIGN PROCESS - AN INTEGRATED APPROACH

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1.0 SUMMARY

The conceptual design of gas turbine engines is a complex process which crosses many engineering disciplines. Aerodynamics, thermodynamics, heat transfer, materials design/selection, and structural analysis are a few of the fields employed when downselecting an appropriate engine configuration. Because of the compexity involved, it is critical to have a process which narrows engine options without missing the "optimum" engine design. The following paper will describe a typical process used at the conceptual design level. Various steps which will be described include propulsion requirements definition, uninstalled engine cycle performance, component design, engine flowpath/weight prediction, installation effects, and the influence of engine design trades on aircraft size and performance. The engine design process is not completely linear. The steps listed above are highly interdependent. A number of iterations are usually necessary in selecting a final engine design. This paper will describe several of the inter-relationships between the various steps.

Frequently, the engine conceptual design process has special considerations which require additional engine analyses. Some modern day examples of these criteria include reduced observables and cost reduction. How these variations are incorporated into the conceptual design process will be discussed.

2.0 INTRODUCTION

The advent of the computer makes early examination of numerous propulsion characteristics possible. Figure 1 illustrates when various computerized techniques became widely available. In the early years of computers, engine selection was based primarily on cycle analysis studies and the design engineer's experience. Other elements such as engine installed performance, flowpath, and weight had to be put off for the detailed design part of the overall engine development process. This could result in the selection of an engine configuration which was not fully optimized. In the worst case, the selected engine could not satisfy the aircraft requirements, necessitating a costly and time consuming redesign. Today, many computerized tools are at the design engineer's disposal to consider component/engine design characteristics, weapon system tradeoffs, and most recently, life cycle cost.

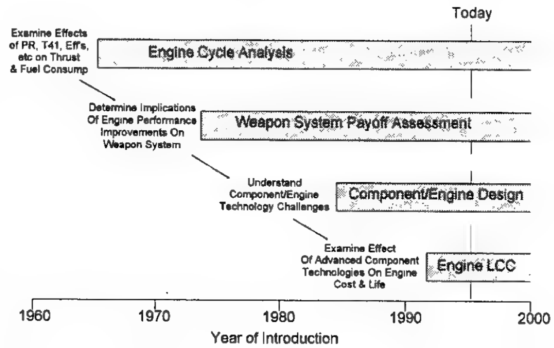

Figure 1 - Historical Trends In Conceptual Analysis Capability

The computer has been a mixed blessing. Because of many different design characteristics which can now be considered at the very early stages of the engine selection process, it is much more difficult to provide a process which can properly address their interdependency. Obviously, there are a multitude of viable approaches to conceptual engine design. The methodology described in this paper is summarized in Figure 2. Each step is covered in more detail in the following sections.

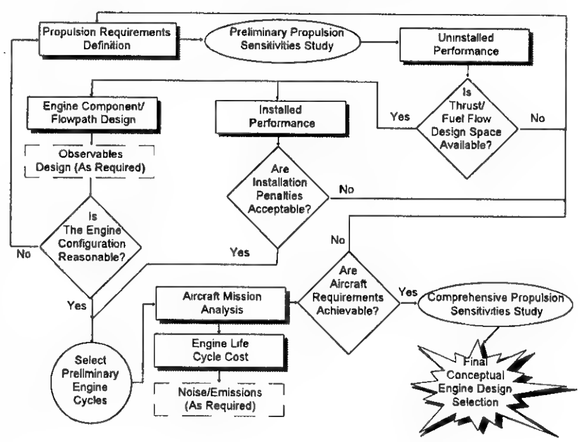

Figure 2 - Engine Conceptual Design Process

3.0 PROPULSION REQUIREMENTS DEFINITION

Perhaps the most critical phase of any development process is right at the beginning -- the definition of requirements. An overconstrained or poorly defined set of requirements can lead

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the design team on a wild goose chase, focusing on the wrong criteria. Unfortunately, at the early stages of an aircraft's conceptual design, the requirements are hard to quantify. Oftentimes, the aircraft user has only a vague idea of what he or she is looking for, i.e., reduced acquisition and maintenance cost, longer range, greater survivability, etc. However, for a successful design, a clearly defined set of requirements right up-front is critical.

In many respects, requirements definition is a mini-conceptual design process. Preliminary propulsion constraints such as combat thrust and cruise fuel consumption need to be established for the rest of the design process to be accomplished. Mission requirements such as range, payload, cruise speed, point performance, endurance, and takeoff and landing restrictions (conventional/short/vertical) must be set. Aircraft weight and dimensional restrictions must be considered. For example, a Navy aircraft is constrained not only by carrier takeoff and landing distance limits, but by the ability to store the aircraft below deck. Elevator weight limits and door opening size place restrictions on aircraft weight and dimensions. These in turn impact the allowable size and dimensions of the propulsion unit. For low observable (LO) aircraft, the engine is a major contributor to the overall aircraft signature. Radar cross section (RCS), infrared (IR), and noise reduction need to be considered in the engine conceptual design process.

A valuable tool to the engine designer is an aircraft sensitivity analysis to engine performance parameters. This provides very preliminary estimates of the impact of thrust, fuel consumption, and engine weight on aircraft range and/or takeoff gross weight. The propulsion designer can use this information to assess engine cycle and flowpath tradeoffs prior to the aircraft mission analysis. The number of potential engine configurations can be narrowed earlier in the process, resulting in shorter overall analysis time.

With reduced resources available to the military, affordability is becoming *the* primary propulsion design criteria for the 90's. Although upfront costs associated with research, development, and acquisition are currently the most significant concern relative to affordability, major emphasis is being placed on support and maintenance aspects of life cycle cost as well. There is a strong desire to utilize existing propulsion systems for future aircraft because of the minimal research and development required as well as the acquisition benefits associated with higher production runs. As far as maintenance is concerned, the Air Force is presently going through a fairly radical transition from a three-level to a two-level system. What this means is that if an engine cannot be repaired on the flight line in a relatively short time, it is returned to the depot. Obviously, improvements in the ability to maintain future engines will be even more important under this new maintenance system.

Historically, environmental concerns have significantly influenced propulsion design for commercial aviation. The Federal Aviation Agency (FAA) has issued regulations which limit both noise and combustion emissions on commercial aircraft. Increasingly, the military is being asked to give consideration to these issues. Even if regulations are not extended to include military systems, good neighbor policies with local and state governments will likely drive future propulsion designers to consider their impact on the environment.

Figure 3 summarizes the myriad of potential propulsion requirements which should be included in the definition of a given propulsion system. Clearly, a great deal of communication between aircraft and propulsion designers is crucial. Unfortunately, because of the lack of information available at this point, most preliminary requirements are set by historical trends and back of the envelope calculations. Updates are necessary throughout the design process as more detailed information becomes available. However, clear requirements definition is key to a successful engine conceptual design.

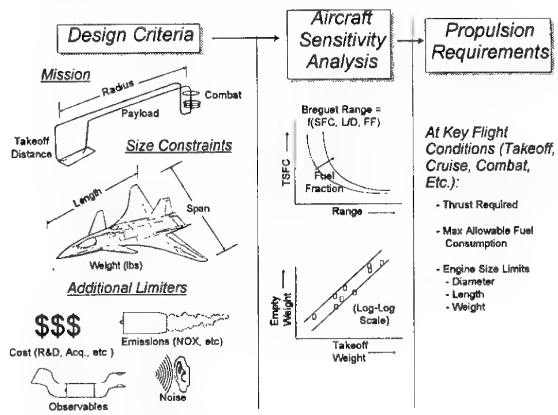

Figure 3 - Propulsion Requirements Definition

4.0 UNINSTALLED PERFORMANCE PREDICTION

Once a reasonable definition of propulsion requirements has been accomplished, the designer can begin to assess the cycle characteristics. For the most common turbine engine in use today, the turbofan, major cycle characteristics include overall pressure ratio, fan pressure ratio, turbine inlet temperature, and bypass ratio (bypass airflow/core airflow). These parameters have the most significant impact on engine performance. The key performance parameters which are used by the turbine engine community are specific thrust (FN/WA) and specific fuel consumption (SFC), which are defined as

Specific Thrust (FN/WA) = Net Thrust/Engine Airflow

Specific Fuel Consumption (SFC) = Fuel Flow/Net Thrust

The larger the specific thrust, the smaller the engine size needed. A small value for specific fuel consumption is desirable, since this implies a low fuel consumption rate.

A distinction should be made between uninstalled and installed performance. At this point in the design process, the engine designer will wish to examine a wide array of potential engine cycles. There could be as many as several hundred combinations of overall pressure ratio, fan presure ratio, turbine inlet temperature and bypass ratio. Because of the large number of cycles involved, it is not feasible to perform a detailed inlet and exhaust system installation for each. Therefore, an uninstalled assessment is performed with standard assumptions made to correct for inlet and exhaust losses. To account for inlet losses, a standard ram pressure loss is assumed to be (based on Mil-E-5007D),

Ram Recovery = 1.0 (Subsonic)
Ram Recovery = $1.00 - 0.076(\text{Mn}-1)^{1.35}$ (Supersonic)

Internal nozzle losses are accounted for typically, and are based on past experience for similar type nozzles (axisymmetric or two-dimensional). These losses are a function of nozzle pressure ratio and area ratio.

To perform the uninstalled performance analysis, a one-dimensional thermodynamic model is used. "Design" point inputs include the cycle characteristics mentioned above as well as component efficiencies, pressure losses, and cooling flows. Oftentimes, more than one flight condition is considered, such as take-off, cruise, and combat. In this case, a methodology is needed to determine component "off-design" performance. This is done through the use of compressor, combustor, turbine and nozzle performance maps which can be scaled to account for variations in airflow and pressure ratio.

A sample uninstalled performance trade study is shown in Figure 4. This example applies to a long range cruise missile. Specific thrust is plotted versus specific fuel

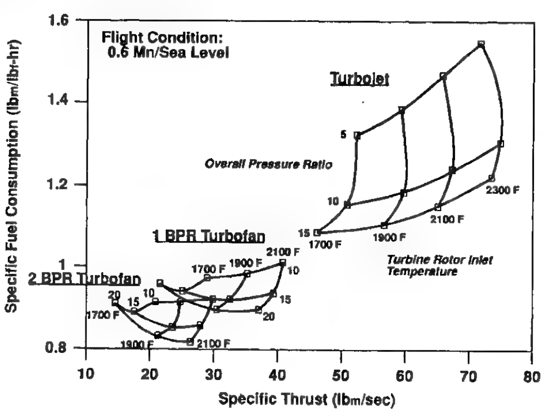

Figure 4 - Uninstalled Performance Trades

consumption for lines of constant overall pressure ratio and turbine inlet temperature. The data is grouped according to bypass ratio. Using this plot, an acceptable cycle design space can be defined. Figure 5 is a repeat of Figure 4 with a typical design space applied. Using the information from the propulsion requirements definition, a minimum specific thrust can be determined based on maximum engine diameter available from the aircraft. Maximum allowable SFC is estimated using required aircraft range. Technology constraints on cycle pressure ratio and turbine inlet temperature further limit the design space. Cost concerns can also play a role in setting the design space. At this point, this is addressed by limiting the compressor and turbine stage count. Hopefully, with all the propulsion limitations applied, there exists a reasonable design space. If there is no design space available, it will be necessary to re-evaluate propulsion design requirements.

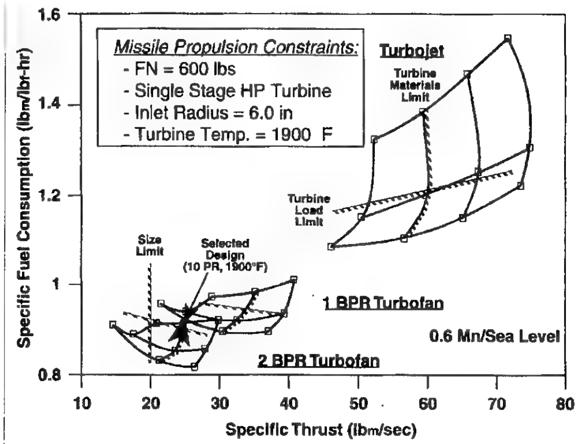

Figure 5 - Unistalled Performance Trades (With Constraints)

At this point, the number of viable propulsion options has been narrowed substantially. With this more manageable number of propulsion options, a more detailed assessment can be performed. The installed performance, component/flowpath design, and observable performance prediction (as required) can be analyzed simultaneously (see Figure 2). This is typically executed by a number of designers who must interact with each other on a regular basis. Each of these design steps will be described separately with the understanding that they have a high amount of interdependency.

5.0 INSTALLED PERFORMANCE PREDICTION

With the number of cycles narrowed, the designer can perform a more detailed assessment of the performance losses associated with integrating the engine with the aircraft. Installation losses cover the effects of the engine/aircraft interaction on the propulsion performance. The installation penalties are typically catagorized into inlet, nozzle internal, and aftbody (or boattail). Several different loss mechanisms make up the inlet penalty: (1) ram recovery, which includes the presure losses due to friction, shocks, and flow separation inside the inlet; (2) spillage, which addresses the mismatch between airflow the engine wants and the inlet delivers; (3) wave drag, which accounts for the external shock losses associated with the inlet lip; and, (4) bleed, which

covers inlet bleed penalties due to boundary layer and bypass bleed flows. Internal nozzle losses include: (1) friction; (2) overexpanded or underexpanded flow due to non-optimum exhaust area; (3) shock losses; and, (4) separation, which can cause severe penalties and is caused by excessive ramp angles or underexpansion. The aftbody is probably the most difficult to predict because it is most closely tied to the airframe. It is influenced by aftbody length, boattail angle, and exhaust jet flowfield interaction with the rest of the aircraft. Nozzle type (axisymmetric or two-dimensional), number of engines, and their proximity to each other also play a part in defining the aftbody penalties.

There are a several ways to adjust uninstalled performance values to account for installation losses. The method which is described in this paper uses a series of inlet and exhaust system tables to correct for the engine integration penalties. Figure 6 provides an overview of the process. The inputs include uninstalled performance parameters (thrust, airflow, fuel flow, nozzle pressure ratio, and exhaust area), inlet and exhaust system maps, and inlet/airframe reference areas. The designer will likely look at the installed performance of a variety of inlets and aftbody configurations before making a final selection. Tradeoffs based on engine flight envelope are required to select the appropriate inlet capture and exhaust nozzle areas. The final output for this step is a definition of installed thrust, airflow, and fuel flow at all the necessary flight conditions.

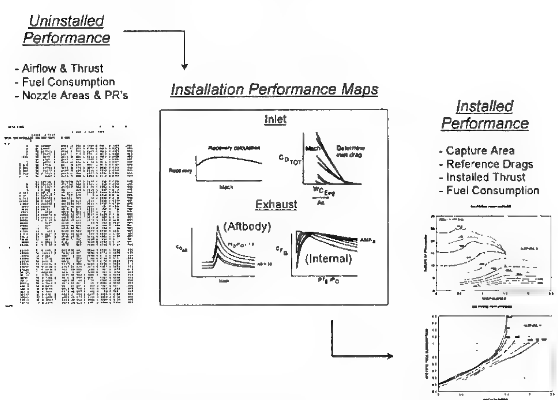

Figure 6 - Engine Installation Process

One more point should be made before moving to the next propulsion design step. The bookkeeping of installation losses can be applied to either the engine thrust or aircraft drag. Because of the interdependancy between the aircraft and its propulsion system, a methodology is required so that no penalties are overlooked or double bookkept. The standard practice is to include a reference maximum power loss with the aircraft drag and lump any additional losses on the installed engine performance. The portion which is lumped with the aircraft drag is commonly referred to as "throttle independent drag". The remainder, which is treated as an installed thrust decrement, is the "throttle dependent drag". Proper bookkeeping of installation penalties can be a sticky issue, particularly if a vehicle does not perform as anticipated. Oftentimes, the customer assesses large economic penalties on the airframe or engine manufacturer for shortfalls in both commercial or military aircraft performance. It is critical that an agreed upon thrust and drag bookkeeping methodology be established and adhered to throughout the design process.

6.0 ENGINE COMPONENT/FLOWPATH DESIGN

Overall component cycle characteristics have been defined, but a more detailed assessment is required to determine engine dimensions and weight. A preliminary look at individual components and how they fit together into an engine flowpath is necessary. Because the component design is largely independent of the installation analysis, both can be performed concurrently. If observables requirements exist, they can have a major impact on the component design. The interaction between observables requirements and their related components must be addressed within the component design process. This could result in several iterations within the step.

The various components which make up a given engine configuration must be balanced in terms of airflows, speeds, and work levels. In order to proceed, the design must begin with one component. For the methodology described in this paper, the fan and compressor are laid out first. The fan and compressor define turbine speeds (RPM) and work requirements. A matrix of compressor designs are examined by varying aerodynamic loading ($gJ\Delta H/U^2$) and stage count. Limits are set which establish the compression system's design space. Usually a compressor is selected based on minimum stage count while not exceeding any design limits. This typically results in the lightest weight and lowest parts count configuration. With the compression system configuration selected, the turbines can be analyzed. As in the compressor, turbine limits are applied to establish available design space. Minimizing turbine stage count is even more important because added turbine stages seriously impact weight, cost, and cooling flow requirements. If no turbine solution space is available, it will be necessary to iterate the compressor design. In addition to loading limits, the high pressure turbine radius should be reasonably close to the compressor radius to align the combustor inlet and exit. The inlet radius of the low pressure turbine should be closely matched to the high pressure turbine exit for similar reasons. The rest of the engine components can now be defined based on their appropriate design limits.

Once the engine flowpath is defined, weights can be computed for the various components. Figure 7 illustrates the component/engine flowpath design process. Specific inputs include:

- Inlet and exit pressures, temperatures, flows, and fuel/air ratios
- Design limits (tip speed, hub speed, blade height, exit swirl, aerodynamic loading, etc.)
- Material definition (type, strength, density, etc.)
- Geometry (aspect ratio, solidity, combustor length/diameter ratio, etc.)

- Special low observables features required (coatings, added cooling, shaping, etc)

Materials are selected down to the engine piece part level (blades,vanes, disks, cases, etc). Airfoil material volume is set by the flowpath analysis, blade solidity (chord/spacing), thickness/chord ratio, and leading and trailing edge thicknesses. Input rim and bore allowable stresses define the disk size. Empirical methods based on case diameter and pressure load are used to establish case thicknesses. Overall engine weight is determined using the density and predicted volume of the material. Weight adders based on empirical data are applied to account for additional features such as variable geometry and cooling.

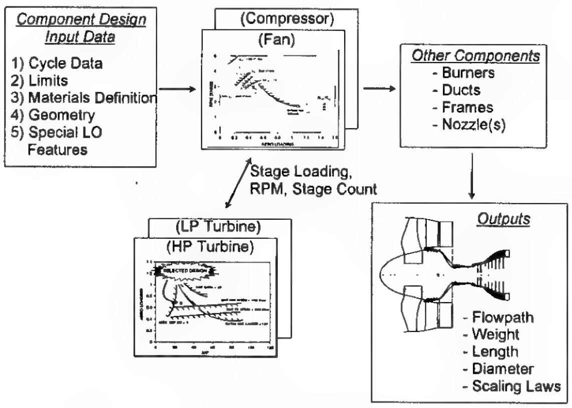

Figure 7 - Engine Component/Flowpath Design

Outputs include overall engine flowpath definition, weight, and dimensions. Since the final engine size which satisfies the mission requirements is unknown at this stage, engine scaling laws are required. The scaling laws provide the ability to resize the engine without having to repeat the component design analysis.

At this point, the number of acceptable engine configurations will likely be further narrowed. Additional engine configurations may have been eliminated because of poor installed performance, excessive weight, or perhaps an undesireable compressor or turbine stage count. As a result, the remaining designs are ready for the next step - the aircraft mission analysis.

7.0 AIRCRAFT MISSION ANALYSIS

At the same time the engine installation and flowpath analysis is being performed, the aircraft and mission have likely been sufficiently refined for propulsion trade studies. The overall aircraft mission analysis process is shown in Figure 8. An Aircraft figure-of-merit is selected such as range, operating empty weight, takeoff gross weight, or endurance. This will be used as a tradeoff parameter, with all other aircraft design parameters held constant, so that the optimum engine configuration can be established. For example, if takeoff gross weight is to be used as a figure-of-merit, the mission range or radius will be held constant.

The mission is broken into segments such as taxi, takeoff, acceleration, climb, and cruise. Each segment must be defined in detail, including such parameters as initial and final Mach number and altitude. Wing area and propulsion thrust sizing criteria are normally set by a number of aircraft performance requirements including specific excess power (P_s), load factor (n), acceleration time and climb rate at key points throughout the flight envelope. Different engines have different sizing criteria due to what is commonly referred to as "lapse rate." Lapse rate is defined as the rate of thrust rolloff associated with increasing Mach Number and/or altitude from sea level static to some pre-defined condition. Higher bypass ratio, higher overall pressure ratio, and lower turbine inlet temperature designs will typically have a higher lapse rate, and hence, poorer performance at increased Mach and altitude. The result is that a larger engine is needed for higher lapse rate designs to satisfy the aircraft's performance requirements.

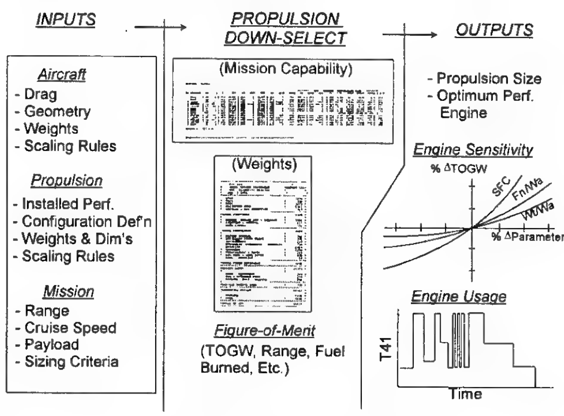

Figure 8 - Aircraft Mission Analysis

The aircraft geometry, weights, and drag must be determined as well. Normally, aircraft characteristics are determined by breaking the aircraft into major subassemblies including the fuselage, wing, tail and engine nacelles (if applicable). Geometry calculations are used to verify that sufficient volume exists for avionics, payload, propulsion, crew compartment, etc. With the aircraft geometry defined, the weights of various aircraft parts can be predicted. Overall drag is the sum of induced, parasite, wave, and trim drag. Also, the throttle independent drag, as described in the Installed Performance Prediction section, is included in the overall aircraft drag.

A number of important propulsion characteristics can be derived from the aircraft analysis. In addition to down-selecting the optimum engine design, required engine size is established. A propulsion sensitivity analysis can be performed to determine the effect of variations in thrust, fuel consumption, engine size and weight on the specified figure-of-merit. A refinement to the optimum engine design may result from the sensitivity analysis.

Also, this analysis is helpful when the designer moves into the propulsion detailed design phase. Sometimes the detailed engine design analysis indicates that the selected engine must be comprimised. The tradeoff analysis can provide the necessary information to determine which propulsion parameter to trade off which will minimize aircraft impact.

Another important piece of information which will result from the aircraft mission analysis is engine usage definition. Throttle excursions, and their impact on compressor exit temperature, turbine inlet temperature, and TAC cycles is critical to predict engine maintenance requirements and life. With engine usage defined, the operations and support cost element of the propulsion Life Cycle Cost (LCC) can be analyzed.

8.0 SPECIAL CONSIDERATIONS

In the past, the selected engine would be ready to transition into the preliminary design phase of development. Recent developments in the world brought on by the perceived diminished threat to national security have resulted in a tremendous change in the military aerospace community. Resources dedicated to national defense are in decline, and as a result, future systems have reduced cost as a key design criteria. The overall Life Cycle Cost (LCC) of an engine can be subdivided into the following catagories:

1) Research & Development (R&D)
2) Acquisition
3) Operations & Support (O&S)
4) Disposal

R&D cost encompasses the expenses associated with bringing the engine into production. Acquisition cost includes the actual production costs to build the fleet. O&S cost covers the fuel and maintenance cost. Disposal cost addresses the costs to remove an engine from the fleet, and is normally not included in the conceptual analysis. The generalized cost prediction process is discussed in the following paragraphs.

From an overall life cycle cost standpoint, R&D cost is comparatively small. However, since the R&D must be accomplished at the beginning of the program, it is a major up-front investment. In fact, because of the high cost of R&D (typically greater than $1B for large man-rated engines), there is the inclination to use off-the-shelf or derivative engines which require minimum development. In addition, technical and manufacturing development problems are largely unpredictable. At the conceptual design stage, R&D costs are typically determined based on past experience corrected to account for engine technology maturity. Anticipated engine testing requirements play a role in defining R&D costs as well. Acquisition cost is the other half of the up-front cost of a new system. This is an ideal opportunity for the manufacturing engineer to impact the engine configuration at the very early stages of the design process. There is a spectrum of approaches to predict acquisition cost. The simplest method is purely empirically based using general cycle parameters such as airflow size, overall pressure ratio, turbine inlet temperature, and bypass ratio. On the other end of the spectrum is a prediction of cost based on individual component manufacturing processes. This involves adding the raw material, fabrication, and man-hour costs for each piece part. Although this methodology provides a more accurate prediction, the complexity of the analysis makes this approach impractical unless the various manufacturing processes are well understood. This approach also requires greater analysis and therefore more time. Whatever the approach taken, the number of engines to be purchased has a large impact on acquisition cost. In general, the more engines a company manufactures, the greater the opportunity to learn better ways to produce an engine. In order to account for this, learning curves are used to account for the number of engines to be purchased.

Engine operations and support (O&S) costs are highly dependent on average flight time and/or TAC cycles during peacetime training, and to a lesser extent, wartime operation. Usage impacts O&S cost both directly through fuel cost, and indirectly through consumption of engine life. Usage is very difficult to predict for a system which has not even been designed beyond the conceptual level. Even if engine performance and life are accurately predicted, how an aircraft is flown is often different than how it was designed to operate. As a result, O&S cost prediction at the conceptual design phase is unlikely to match very well with the actual O&S cost. However, O&S cost predictions can be a valuable tool in comparing various potential engine designs. It can also be helpful in comparing new systems to existing aircraft performing similar missions.

To predict O&S cost, several system level assumptions must be made. These assumptions include aircraft fleet size, aircraft life, and usage per month in terms of flight time and/or TAC cycles. To determine cost, the designer essentially adds up the total engine usage. Scheduled and unscheduled maintenance actions are predicted from this usage estimate, and total number of engines required (including spares) is determined. It should be kept in mind that fuel cost is a major portion of engine O&S cost, typically over 50%.

For the design process described in this paper, the assumption has been that cost analysis is accomplished after the aircraft mission analysis. Recent development of computerized tools will likely move cost analysis forward in the design process. This is particularly true in the case of R&D and acquisition cost, which is not as dependent on overall aircraft system usage and force structure. It is anticipated that upfront costs will become an integral part of the component/flowpath analysis.

One other item deserves a brief mention - Engine emissions. For the purposes of this discussion, emissions include both noise and combustion products (smoke, NOX, CO, and hydrocarbons). Local communities have become increasingly critical of the military's environmental impact. Although it is unlikely the military will give up their performance edge, future designs will have to give consideration towards reduced noise and combustion emissions. Emissions could well become the

next element to be incorporated in the engine conceptual design process.

9.0 CONCLUDING REMARKS

This brief synopsis is intended to provide an overview of the interrelationships between various propulsion conceptual design steps. Computerized conceptual design tools exist to analysis uninstalled performance, installed performance, component/flowpath design, aircraft tradeoffs, and engine life cycle cost. Noise and combustion emissions could very well become the next elements to be integrated into the process. Whole books have been written to address each of these steps, so this paper cannot possible cover all issues. Hopefully it has at least introduced the reader to tools which are currently available..

Many different methods exist to integrate various design elements into an overall process. Ideally, designers like to perform all design steps concurrently. However, several steps must be performed in series since results of one must feed into the next. Installation and component design analyses can be performed simultaneously, and the hope is that up-front costs (R&D and acquistion) can be integrated into the process at an earlier stage.

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COMPUTATIONAL ASSESSMENT ON INTEGRATED ANALYSIS & DESIGN

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ABSTRACT

One important question in Analysis & Design is **¿how much Error (e_N) has the Solution (x_N)?**. The answer is very difficult even if limited strictely to the Computation.

For two decades the Author has researched & developed a **Procedure** in the University & the INTA to give an answer acceptable to Industry.

This paper gives the Fundaments & the **Applications** to two Aerospace Projects:

1. Airplane: $C_{L\alpha}$ (C_L slope)
2. Satellite: λ_{min} (min eigenvalue)

whose Solutions (x) are Unknown, but they can be Computed plausibly, as shown. (See Notation).

0. NOTATION

Symbol	Meaning
e_D	Discretización Error
e_n	n Error
e_N	Final Error
r	Limit Rate
r_n	n Rate
r_N	Final Rate
x	Limit Solution
x_n	n Solution
x_N	Final Solution
Δx_n	n Increment
Δx_N	Final Increment
=	Mathematical Equality
~	Computational Equality

(See next for definitions)

1. INTRODUCTION

This Procedure may be summarized as follows. In order to estimate the Error (e_N) we must produce some Sequence $\{x_n\}$ and truncate it at some $_n = _N$, that is at some Solution x_N.

Let $\{x_n\}$ be some given Numerical Sequence $x_n \in R$ and N some **unknown** natural integer **defined** as the first value of n that verifies:

$$x_{n+1} \sim x_n \tag{1}$$

where ~ stands for a **Computational Equality** that takes place when both sides of it are identical up to the Floating Arithmetic used, so that it depends on the Computer Precision (t) as much as the Machine Epsilon (ε) does.

The Computational Test (1) is a Necessary Condition for Convergence, but Not Sufficient in general, because it only says that the **Increments, defined** by ($_n = 0, 1, \ldots$):

$$\boxed{\Delta x_n = x_{n+1} - x_n} \tag{2}$$

are almost zero for $_n = _N$ as it is well known (harmonica, and so).

The NECESSARY AND SUFFICIENT CONDITION for Convergence is:

$$x \sim x_N \tag{3}$$

so that the **Truncation Error, defined** as:

$$e_n = x - x_n \tag{4}$$

(where x is the Theoretical Limit), is small enough at $_n = _N$ that is:

$$e_N \sim 0 \tag{5}$$

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

The Computational Test (3) is not feasible (except in trivial academic cases where x is known) but its equivalent (5) is generally applicable as discussed here, noting again that the theoretical and practical limitations of any of those procedures prevent us to perform it exactly but should not prevent us to make the best possible use of it in the real industrial cases.

The relevant question is to estimate e_N as well as possible and the answer may be to sum the Rest of the Series:

$$x = x_0 + \Delta x_0 + \Delta x_1 + \ldots\ldots + \Delta x_N + \Delta x_{N+1} + \ldots \quad (6)$$

that is (from (4) and (6)):

$$e_N = \Delta x_N + \Delta x_{N+1} + \ldots\ldots \quad (7)$$

The procedure presented here starts from this point on, assuming that (1) has been verified computationally, so that $_N$ is fixed, that is x_N seems to have settled down, as usual; then introduces the **Rates defined** as ($_n$ = 1, 2, ...):

$$\boxed{r_n = \Delta x_n / \Delta x_{n-1}} \quad (8)$$

so that (7) becomes:

$$e_N = \Delta x_N\,(1 + r_{N+1}\,(1 + \ldots\ldots\ldots)\ldots\ldots)) \quad (9)$$

• **The first important point** is that now we need only to assume that r_N has ALSO settled down to sum (9) inmediately as a Geometrical Series (which converges if $-1 < r_N < 1$) giving:

$$\boxed{e_N \sim \Delta x_N / (1 - r_N)} \quad (10)$$

where we use the Computational Equality sign but in some trivial cases it will be the mathematical one (r_N constant).

• **The second relevant question** is that, in addition, r_n has a KNOWN Theoretical Limit r that depends on the Application as illustrated now so that we can verify computationally whether we are near enough to that value or not.

IN CONCLUSION: Given $\{x_n\}$ and r, we only need to produce $\{\Delta x_n\}$ and $\{r_n\}$ -which is straightforward from their definitions (2 & 8) and to get $_N$ so that r_N have settled down to r- which is also straighforward as shown next.

This paper describes this Procedure in order to build $\{x_n\}$ and r in two particular cases common in the Aerospace Industry named before: the goal is to assess (or not) that the Error (e_N) is small enough **before the Experimentation is done in order to save time and money in the Project**. (See References).

2. DISCUSSION

Analysis & Design is based on Mathematical Models & Numerical Methods that are essentially approximate. Even in these Stationary cases (see next) there are, at least, **Discretization Errors** that essentially take the form:

$$e_D = C_p\, h^p \quad (11)$$

were C_p is a function (some derivative) p is a constant (some natural) and h is a parameter (some fraction) that **cannot be fixed analitically and a priori**.

This Paper is based on **h-Refinements** that essentially take the form:

$$h_{K+1} = h_K / \beta \quad (12)$$

where β is a constant (some natural greater than 1). Admiting that C_p tends to a constant (neither zero nor infinite), defining:

$$r = \lim_{K \to \infty} \frac{e_K}{e_{K-1}} \quad (13)$$

we have from (11) & (12):

$$\boxed{r = \beta^{-p}} \quad (14)$$

were β & p are generally known in advance, and:

$$0 < r \leq \frac{1}{2} \quad (15)$$

for any β (≥ 2) & p (≥ 1) so that $\{x_n\}$ converges to x at the Linear Rate r (See References).

2.1. APPLICATION 1

The first Application will be one from Aerodynamics. Namely the Computation of the Wing $C_{L\alpha}$ through a Method of Panels: $p = 1$, $\beta = 2$. The initial question is reduced to **¿how big must h be so that the Error is less than 5% 1/rad?**

The Figure 1 shows the Wing & the Panels: NC is the number of Panels along the chord (being fixed each time). NE is the number of Pannels along the span (being refined) h-Refinement is 1D (not 2D) $h = h/2$ ($n = 2n$).

The Tables 1 use $n = NE = 1/h$ and show that **r_n converges to $r = 0.5$ that is 2^{-1} as expected,** for NC = 2 to 16 (Number of Vortex-Lattice by Chord). All show the same normal trend: **Convergence is Assessed; error is acceptable.**

2.2. APPLICATION 2

The second Application will be one from Structures. Namely the Computation of the Satellite λ_{min} through a Method of Elements: $p = 2$, $\beta = 2$. The question is similar **¿how big must h be so that the Error is less than 5% Hz?**

The Figure 2 shows the Satellite & the Elements: NET is the total number of Elements (being quadrupled each time). F is the frequency in Hertz (not $\lambda = (2\,\pi\,F)^2$) h-Refinement is 2D, $h=h/2$ ($n = 4n$).

The Tables 2 use $n = NET = 1/h^2$ and F instead of λ but **r_n does not converge to $r = 0.25$, in any case.** All show the same abnormal trend: **Convergence is Not Assessed; error is Not acceptable.**

3. CONCLUSIONS

• In Integrated Analysis & Design, after any Analysis, comes an important question: ¿how **good** (or bad) are the Results?

• Computational assessment shown above is a plausible answer that proves the utility of this Procedure in Industrial Analysis & Design in general, and in the Integrated one in particular, as shown here: it is **convenient**.

• This Procedure applies equally to Aerodynamics (Panels) and to Structures (Elements) either to Statics or to Dynamics, as shown in the References: it is **universal**.

• Real Experiments must be based on Approximate Solutions Previously Assessed in order to not only compare rigorously Computation & Experimentation, but also spare Time and Money in Integrated Analysis & Design: it is **evident**.

• In conclusion, in the first Analysis the Results are sound & $C_{L_\alpha} \sim 2.43$ is plausible, but in the second Analysis the Results are not sound & F is not plausible: it is **recommended** to enhance the second Design **before** Experimentation.

4. ACKNOWLEDGEMENTS

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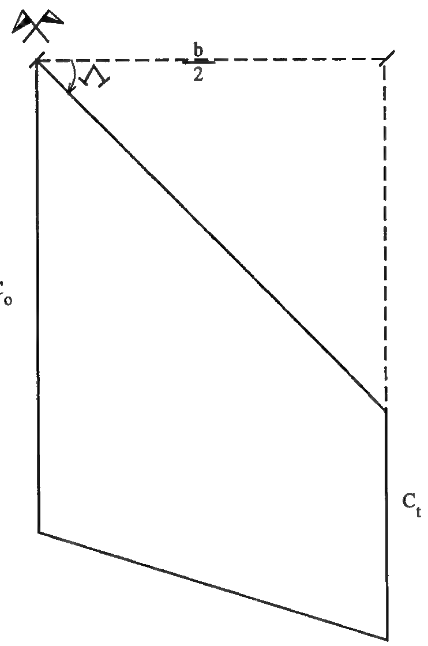
Figure 1

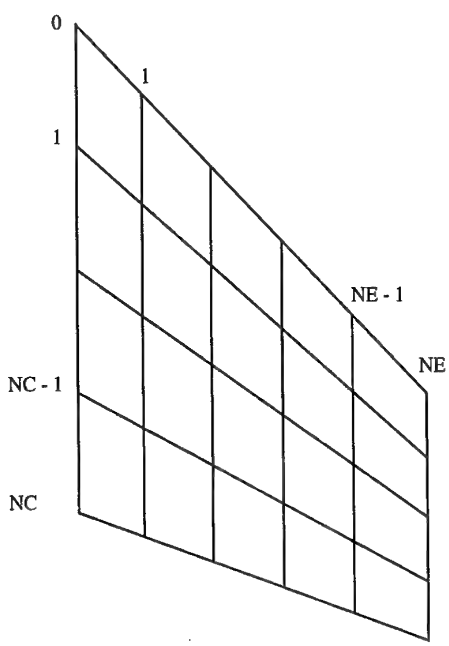
a) Half Wing GEOMETRY

(b, C_o, C_t, Λ, Scaled)



b) Half Wing PANELS

(NC, NE, Constants)

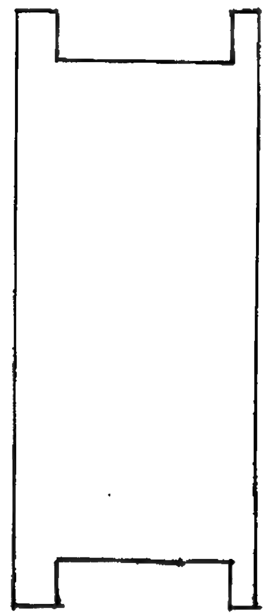


Program of NASA TN D-7921

Figure 2

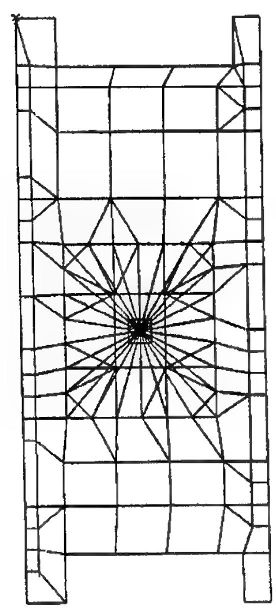
a) Platform GEOMETRY

(Scaled)



b) Platform ELEMENTS

(NET, Bilineals)



Program MSC/NASTRAN

Tables 1

Table 1.1 (NC = 2)

n = NE	$x_n = C_{L\alpha}$	Δx_n	r_n	**Observation**
2	2.81463	-.18557	--	
4	2.62906	-.10854	.58	
8	2.52052	-.06048	.55	$\lvert\Delta x_n\rvert \ll x_n$
16	2.46472	-.02809	.46	$r_n \sim r$
32	2.43663	--	--	Converged
∞	$x_1 = 2.40\underline{8}$	0	r = .50 (p=1)	Extrapolated

Table 1.2 (NC = 4)

	2.81351	-.17957	--	
	2.63394	-.10286	.57	
id	2.53018	-.05619	.54	id
	2.47489	-.02835	.50	
	2.44654	--	--	
	$x_2 = 2.41\underline{8}$	0	r = .50 (p = 1)	Extrapolated

Table 1.3 (NC = 8)

	2.81359	-.17936	--	
id	2.63423	-.10054	.56	
	2.53369	-.05408	.53	id
	2.47961	--	--	
	$x_3 = 2.42\underline{5}$	0	r = .50 (p=1)	Extrapolated

Table 1.4 (NC = 16)

	2.81361	-.17929	--	
id	2.63432	-.10030	.55	id
	2.53402	--	--	
	$x_4 = 2.43\underline{3}$	0	r = .50 (p = 1)	Extrapolated

Tables 2

Table 2.1 (1st frequency)

NET	F	Δ	r	Observation
225	61.218	-1.110	---	$\lvert\Delta x_N\rvert \ll F$
900	60.108	-1.071	0.96	$0 < r_N < 1$
3600	59.037	-0.947	0.88	$r_N \neq r$
14400	58.090	---	---	ANOMALOUS

Table 2.2 (2nd id)

	74.371	-1.650	---	
id	72.721	-1.327	0.80	id
	71.394	-1.066	0.80	
	70.328	---	---	

Table 2.3 (3rd id)

	82.338	-1.488	---	
id	80.850	-1.379	0.93	id
	79.471	-1.136	0.82	
	78.335	---	---	

Table 2.4 (4th id)

	145.500	-0.958	---	
id	144.542	-0.780	0.81	id
	143.762	-0.762	0.97	
	143.000	---	---	

GLOBAL/LOCAL ANALYSIS IN FINITE ELEMENT TECHNOLOGY

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SUMMARY
In the design and verification of complex structures the global analysis gives the internal load paths, whereas the local analysis computes stresses and strains. These analyses are performed using classical methods, the Finite Element Analysis (FEA), or a combination of both. The outstanding development in finite element methodology and the explosion in computer hardware capability led to apply directly the FEA techniques to global and local analyses, with reduction of computation time and improvement of results accuracy. This paper explores some of the FEA practices currently in use, focusing on work presently being performed in Alenia Spazio.

INTRODUCTION
In studying the structural behaviour of a complex assembly, the first attempt is to determine overall characteristics, such as vibration frequencies, load paths, general stiffness or deformed shape. To obtain these data a coarse mesh finite element (FE) model is usually sufficient. This is referred to as the "global model", representing the complete structure.

The global model may be used to determine stresses when stress gradients are low. However, due to discontinuities (such as interfaces, reinforcements, welds, etc.) the global model is no longer adequate to provide accurate stresses at these localized areas. To obtain stresses in these areas, either rigorous classical methods using internal forces from the global model or finer mesh models are used. These models are referred to as "local models", representing localized areas.

Local models are also used to study complex structural behaviours restricted to some areas, such as local buckling, contact phenomena, material and geometry nonlinearity, where the use of the global model is impracticable. For example, generally in pressure vessel design, in the vicinity of aforementioned structure discontinuities, large relative displacement can occur, requiring a local nonlinear analysis.

The increasing use of the global/local FE approach in industry has been made possible due to development of some special techniques: e.g. the automatic mesh generation and model integration techniques. The software improvement pushes moreover to use accurate FE models, continuously increasing the number of degrees of freedom (DOF) and the simulation complexity. The availability of powerful hardware resources allows to deal with global/local analysis demands, with cost and time reduction.

In this paper some global/local examples are provided from Alenia Spazio industry applications. FE techniques will be presented with reference to the structural analysis of the Mini Pressurized Logistics Module (MPLM), for the International Space Station Alpha. Global and local models interfacing, displacement and force compatibility methods, reduction and assembling techniques, and superelement methodology are discussed, on the basis of MSC/NASTRAN users's experience. Additionally the attention is focused on several FEA advanced technologies which promote the improvement of local analysis, for example: geometric modelling and CAD-CAE link, error estimation, adaptive meshing, and p-element technology.

Paper presented at the 82nd Meeting of the AGARD SMP, on "Integrated Airframe Design Technology", held in Sesimbra, Portugal, from 8-9 May 1996, and published in R-814.

GLOBAL/LOCAL ANALYSIS OF THE MINI PRESSURIZED LOGISTICS MODULE

The MPLM is a carrier module used to transfer payloads to/from the Space Station (Fig. 1). The payloads are allocated into the racks. Different racks layouts are possible and a maximum of 16 racks can be installed.

The overall structure has been represented by a relatively coarse mesh model (Fig. 2), with 61000 active DOF. This model has been used for both load paths static analysis and dynamic coupled load analysis (CLA) of MPLM as mounted in the Shuttle cargo bay.

The global model construction takes into account the following:

1)the global model incorporates some results of local analyses,

2)the global model is built by assembling several sub-models.

An example of the first case is given by the analysis of the five pins that support MPLM in the Shuttle cargo bay. These pins are named trunnions and their respective housings are named bodies. The trunnion has been simply represented by linear beam elements in the global model, whereas the body cannot be easily represented, being a massive machined piece. Then the following approach has been applied. A local FE model of the trunnion and the body has been developed (Fig. 3), including the pre-loaded bolt that retains the trunnion into the body. Solid elements have been used and contact phenomena between trunnion and body have been taken into account. The flexibility of the trunnion/body assembly has been accurately evaluated by this local solid element model and then it has been introduced into the global model, defining properly the stiffness of the trunnion beam elements.

As regards to sub-models assembly, the racks integration is a good example. The rack mathematical model is a very fine sub-model of 45000 DOF. As noted before, a maximum of 16 racks can be installed into MPLM, and therefore up to 16 rack models must be integrated into the global model. Reduction/assembly techniques allowed to overcome the problem of an unacceptable increase of DOF. For static analysis a static condensation of the rack model to 135 DOF has been used. For dynamic coupled analysis the Craig-Bampton method [1] has been adopted: each rack has been reduced to 50 modal components and has been assembled into the global model, by using the modal synthesis technique.

In the above example, the global model has been developed following a procedure "from local to global", by using local analyses results and assembling sub-models. In the following example, starting from the global model, the attention has been focused in some local areas. A reverse procedure has then been applied, "from global to local model", i.e. the information given by the global model has been taken as input to the local model.

In this example, the friction analysis at trunnion/Shuttle interface is considered. Three of the five MPLM trunnions are supported by slides on Shuttle cargo-bay. These slides do not prevent motion of trunnions in the direction of MPLM longitudinal axis, the friction effects apart. Friction longitudinal forces can be developed up to 10% of the trunnion normal reaction forces. Due to the static redundancy of trunnion reactions, the module stiffness is important for friction analysis and hence dictates the use of the global model. Because the friction effects are nonlinear phenomena restricted to a very limited area, a full model nonlinear analysis is not practical. The reduction technique has been again the preferred method to represent correctly the MPLM stiffness, the complete global model having been reduced only to the five trunnion/Shuttle interface points. To represent friction, gap elements have been used to support these points.

Local nonlinearity is a common situation in pressurized welded modules. Firstly, geometrical nonlinear effects are typical of shells under pressure. In MPLM, for instance, in evaluating the cone/cylinder discontinuity it

has been necessary to consider geometrical nonlinear behaviour. In the linear and nonlinear analyses, differences of 15% can occur on stresses, and the shape of the deformed geometry can be significantly affected. In this case, a dedicated solid element local model allowed an accurate stress analysis to be performed.

Consideration of geometrical and material nonlinear effects has also been necessary in the calculation of stresses in cones under internal pressure loading. The linear analysis predicted 20% higher stresses in ribs and erroneous results at the location of weld seems at ultimate pressure. In the case of weld analysis, the 2219 parent material has the mechanical properties of the T851 heat treated state, whereas the welded material is at T0 annealed state. Therefore, the construction of local cone model must be fine enough to represent welded and heat affected zones in order to consider their proper material stress/strain curves.

Several other local models have been built in MPLM analysis. They are designed to recover stresses or to evaluate accurately the stiffness. The rack attachment blocks, the fittings, the longeron/ring bolted joints, the cylindrical waffle panel are examples of detailed stress models. The grapple fixture supporting structure is a very detailed model to evaluate frequencies of MPLM retained only by Shuttle operating arm, during berthing to the Space Station. The hatch bulkhead local model has been used to verify the requirements on relative displacements at interface between MPLM and the Space Station. Detailed shell models are also used for buckling calculations (Figs. 5 and 6). The Figs. 7 and 8 show some examples of local models. The Fig. 9 shows the location of several of these local models on the global MPLM model.

In Fig. 9 some examples of solid FE models are also shown. They are used when it is important to represent exactly the geometry of the structure to perform an adequate stress analysis, as for instance in the aforementioned discontinuity analysis of cone/cylinder ring. In solid FE models the p-element technology is sometime preferred with respect to the traditional h-element method. In fracture mechanics, for example, solid p-element are used to correctly determine the stress intensity factor for cracked ribs on cylinder waffle panels. The Fig. 10 shows an analysis of this type.

Solid FE are usually necessary in studying contact phenomena. The trunnion/body analysis is an example already presented. The bolted flange of the aft access closure is another example of this type (Fig. 4). In this case, an accurate displacement analysis was required to verify that the relative opening between the two flanges does not exceed the seal design allowable value of 0.5 mm, under an internal pressure of 15.2 psi. A solid FE model has been used, representing a half pitch of the bolted flange and a half bolt, taking advantage of the structure symmetry. The preload in the bolt is simulated by thermal stresses. The contact between flanges and bolt is considered, including friction. Geometry nonlinear effects are also taken into account.

ZOOMING TECHNIQUES

As summarized in [2], in current literature the phrase global/local method has been defined differently by different authors. On the basis of MPLM experience, it seems important to underline the following aspects, that can contribute to a proper definition. The need to build local models is not only due to the necessity of mesh refinement. It is true that the mesh refinement is an important aspect in any kind of analysis (both global and local), but it is more appropriate to describe "zooming technique" as the methodology of building more and more accurate models, for a better data recovery. Whereas the most characteristic aspect of the global/local methodology is on the study of local phenomena that can influence and/or can be influenced by the behaviour of the full structure and hence requiring a very accurate representation. Therefore a "global/local technique" can be defined as the study of global and local behaviours, where results or contributing influences from either one of these analyses are

accounted for in global or local models, depending on the type of analysis being performed. In "zooming" the main considerations are the fine mesh generation, the mesh transition, the error estimation and the comparison between p- and h-technology. In the case of the "global/local" method the main emphasis is on the models assembling procedures.

The necessity of a finer mesh in some cases is clearly evident. For example, the MPLM global model represents the waffle panels by using only shell elements having orthotropic equivalent properties with smeared ribs. In the regions where the ribs progressively run out and are discontinuous it is necessary to represent the correct position of the ribs with respect to the surrounding structural components (e.g. longerons, rings, welds etc.) in order to recover the stresses directly from the model. To accomplish this, several detailed models of waffle panels have been developed by representing correctly the waffle pattern with discrete ribs.

In some cases an "a priori" judgement does not suffice and error analyses can decide if a finer mesh is required. In today's commercial codes several error estimate methods are available, e.g.: the strain energy, the stress gradient, the Von Mises stress. More simply a good practice is to compare the stress value at the centre of elements (or at the Gauss points) with stress value interpolated by the post processor at the nodes (commonly known as "contour plots"). When the differences between these two values are judged too large, a refinement of the mesh is required.

When the need of zooming has been recognized, the problem is to build the fine mesh in the most efficient way. The automatic mesh generation is the obvious choice. Some analysis codes employ built-in mesh rezoning features. However the more common way is to use an interactive graphic pre-processor. In this case automatic mesh generation is preferred, but a geometric definition of the structure must exist, in terms of lines, surfaces and volumes. It is therefore important that the pre-processor have adequate capability to handle geometry. Often it is more convenient to transfer geometry directly from CAD to CAE. If a solid modelling is used by CAD, the complete geometry description by volumes is available. The most common situation in space engineering is to use only surfaces. Anyhow 2D drafting on CAD systems are also a good starting point for the CAE activities. Lines and surfaces can be transferred via IGES files.

MESH INTERFACING

The interfacing of fine and coarse meshes is the next aspect. The nodes of the coarse mesh do not match the nodes of the finer mesh, except for a few nodes. These nodes can be merged, but it is not recommended to leave the nodes which are not coincident unconnected, because loss of stiffness and stress field perturbation can arise. One of the following two methods is preferred:

a) to build a transition mesh between coarse and fine meshes, or
b) to link nodes of coarse and fine meshes by means of multi-point-constraints (MPC).

Transition meshes can be built in different ways. With reference to the shell elements, the following ones are possible:

1) to employ "free mesh" algorithms available in pre-processors,
2) to use triangular elements and/or quadrilateral elements with an additional intermediate node on the edges (QUAD8 element in MSC/NASTRAN).

Examples are given in Fig. 11.

Different MPC methods are compared in [3] and an interpolation method is recommended (named RSPLINE in the MSC/NASTRAN code).

From a practical point of view the following remarks are important:

- because the graphic preprocessors usually make possible the option of automatic mesh changing (with or without triangles), as well as interactive definition of MPC, both methods can be easily applied;

- although the mesh transition method can cause element distortion, but the mesh can visually inspected and preprocessors automatic features can be used to check the elements quality; whereas the MPC method can cause less evident mistakes in DOF relation definition;
- mesh interfacing produces perturbations especially on internal forces, such that stress recovery close to the interfacing zones is not recommended.

MODEL ASSEMBLING

As explained above, the most specific aspect of the global/local analysis is the assembling of different models. The mesh interfacing is only the minor aspect. The main emphasis is on how to make global and local models interact and the transfer of pertinent information between them.

To integrate global and local models the following three methods are possible:
1) the displacement compatibility,
2) the force compatibility,
3) the displacement and force compatibility.

In the methods 1 and 2 the global model is analysed first, with a coarse mesh for the zone to be refined. This run computes both forces and displacements at the boundary of that zone. Then the local model with refined mesh is separately run, by imposing on its boundary the computed displacements (displacement compatibility) or forces (force compatibility) from the global model. Due to the different stiffness of the refined zone models, the forces obtained in displacement method do not match forces from global model. Similarly, in the force compatibility method, the displacements on the boundary of the local model do not match corresponding displacements of the global model.

To apply the displacement or force compatibility methods , it is sufficient to run separately the local model, by specifying displacements or forces at the boundary. However, as suggested in [4], the superelement method can be efficiently used both by the first and the second method. The basic idea is to provide both coarse and fine model of the same zone as different superelements. The coarse model is used in reduction runs, while the fine model is used in recovery. A change in local model does not request reanalysis of the global model.

The superelement method can be used more efficiently to obtain both displacement and force compatibility. In this case the fine model is also used in reduction phases and the correct stiffness of the model is taken into account both in reduction and recovery. The rest of the structure can be also partitioned in other superelements, that are reduced to a "collector" superelement. The residual structure is the boundary between the collector superelement and the refined model [4].

There are some situations where the superelement method is difficult to be used, as discussed in [5]. The analysis of nonlinear effects and buckling in local areas are important examples of this type. In both of these cases the local regions must be placed in the residual structure, and this results in very expensive runs.

The superelement method is in any case a complex application, because it requires structure partitioning, planning of runs and relevant disk area for permanent databases. For these reasons it has been often preferred a more simple "reduction/assembly technique". The global model is statically condensed to boundary nodes of the local model and eventually to few other nodes (e.g. the constraint nodes). As a result of the static reduction runs, the mass, stiffness and load matrices are obtained to represent the global model. These matrices can be assembled into the local model matrices. New local model modifications do not require the reduction of the global model again. The above procedure can be reversed, i.e. detailed local model is condensed and assembled into the global model. The major disadvantage of reduction/assembly method is that data recovery is not possible for the condensed structure.

The reduction/assembly technique requires an experienced user of the codes, since it will be necessary to employ some user developed procedures. For example, MSC/NASTRAN alterations and procedures were developed by Alenia Spazio (by using the DMAP language) to allow assembling of reduced structures. For this reason the evolution of the global/local methodology led to assemble directly the local model into the global model, without any reduction (Figs. 12 and 13).

This approach has been possible because not only the hardware development offers today powerful CPU resource at low cost, but also the code evolution itself employs much more efficient solver techniques. An example is given by the sparse matrix solvers [6], that can cut down CPU requests more than 10 times. For example, the MPLM forward cone detailed model, when assembled into the global model, results in a model of 23000 nodes and 125000 active DOF. A linear static analysis took 1200 CPU minutes on HP 700 workstation with direct conventional solver, whereas only 70 minutes are required using the sparse method.

This method of integrating directly the physical models, clearly is not always applicable. This is true especially when special analyses are requested, as buckling and nonlinear analyses. But it is important to underline that linear statics accounts for major percentage of all the analyses performed in structural engineering. Thanks to hardware and software improvements, the practical limits on active DOF in linear static analysis has been enormously increased. As a consequence traditional techniques as that based on superelement and reduction/assembly, can often be avoided for simplicity and user friendliness.

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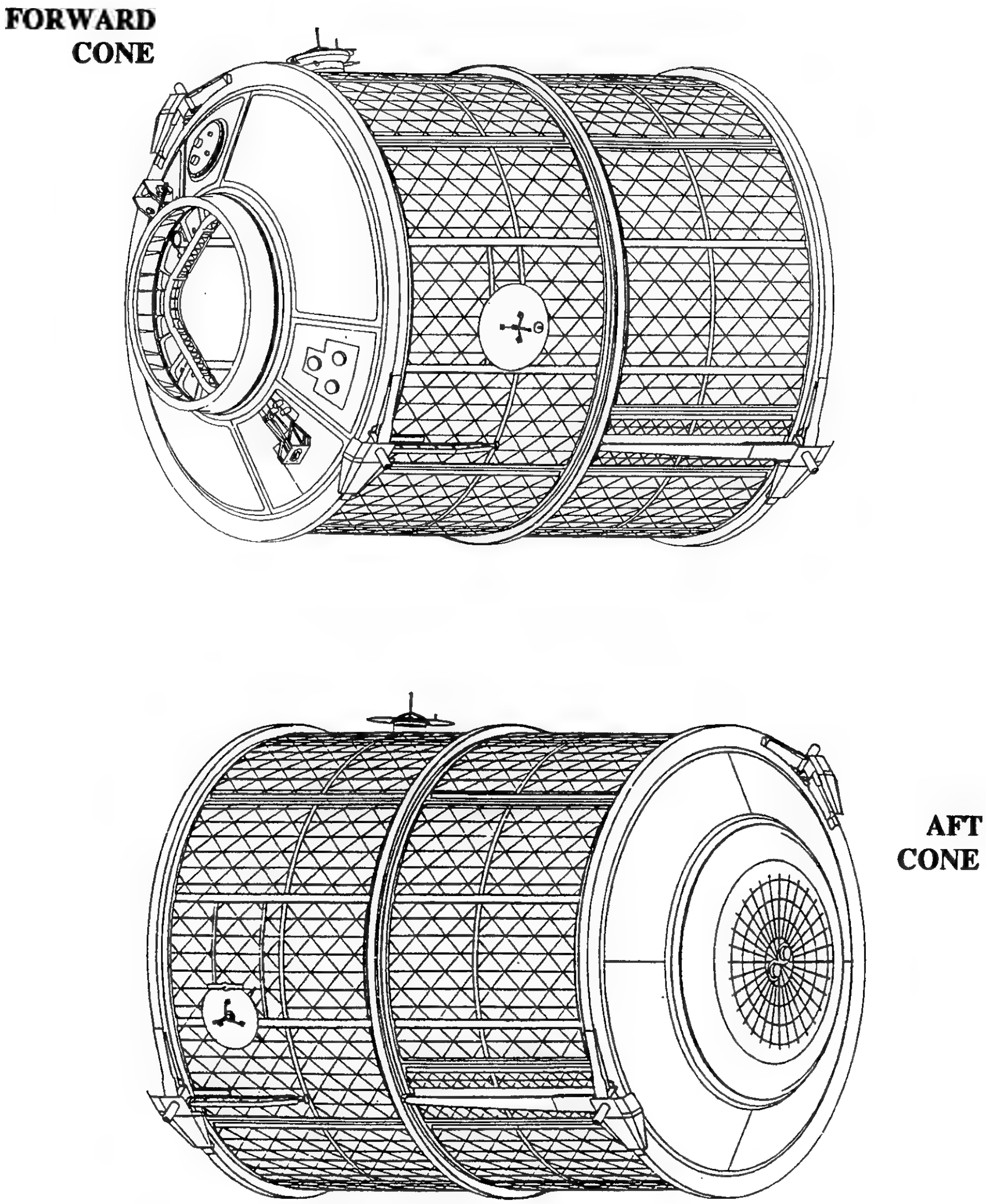


Fig. 1 The Mini Pressurized Logistics Module (MPLM)

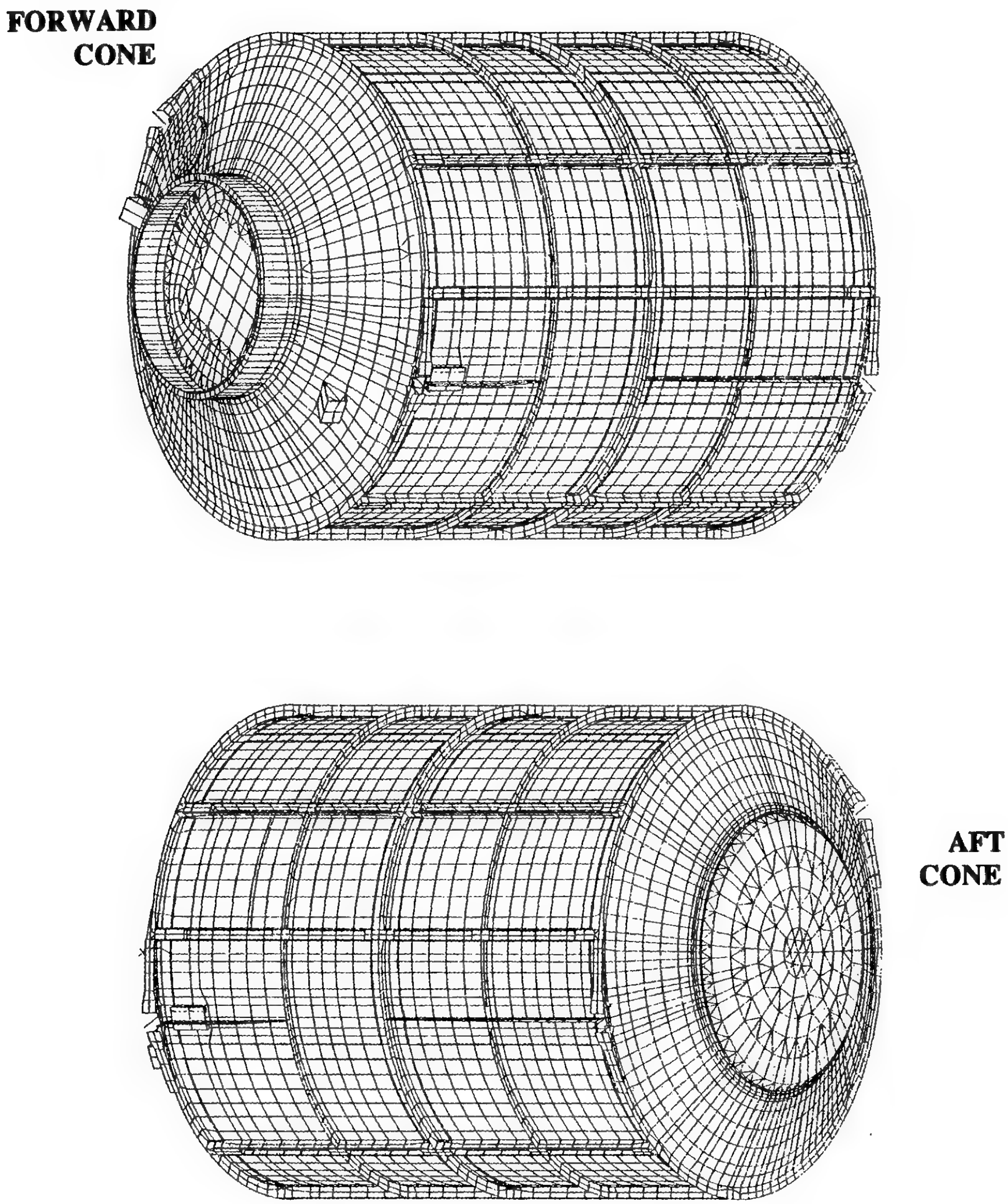


Fig. 2 The MPLM Global Model

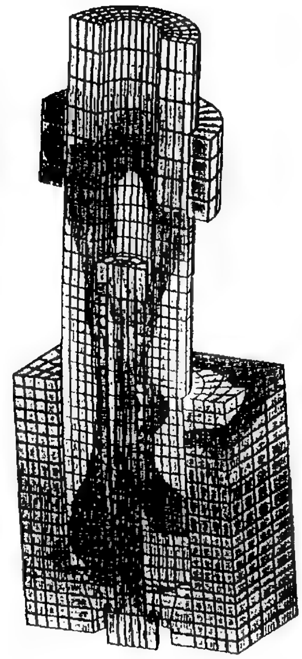


Fig. 3 Trunnion/Body Model

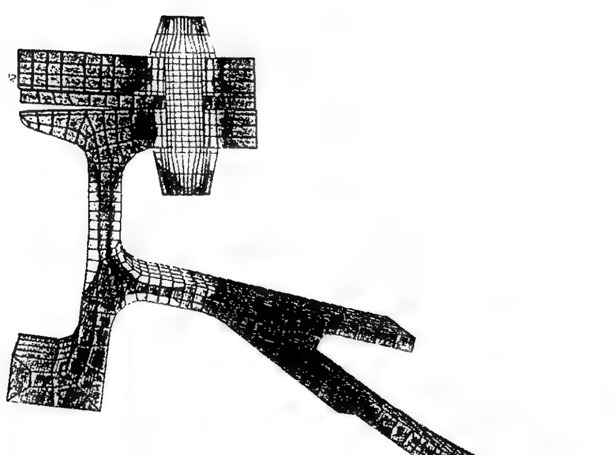


Fig. 4 Aft Cone/Access Closure flanges Model

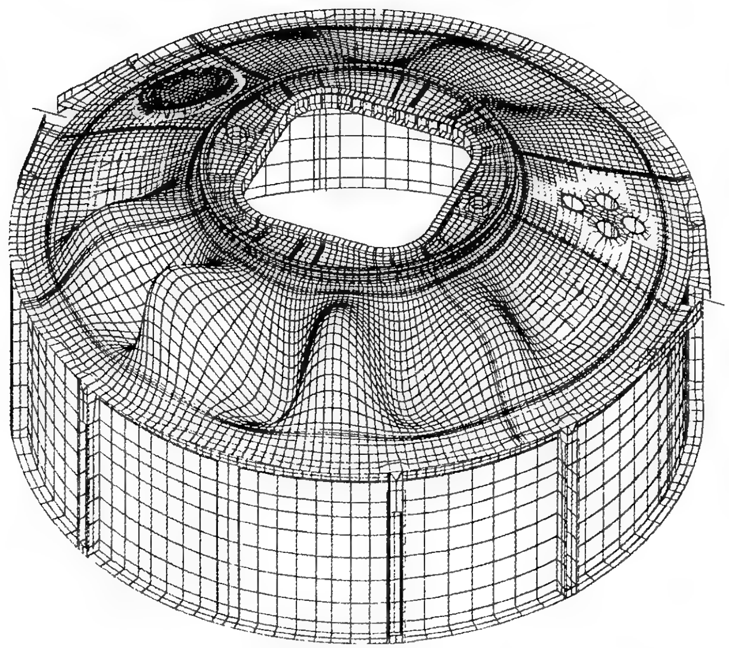


Fig. 5 Forward Cone Model (Buckling under external pressure)

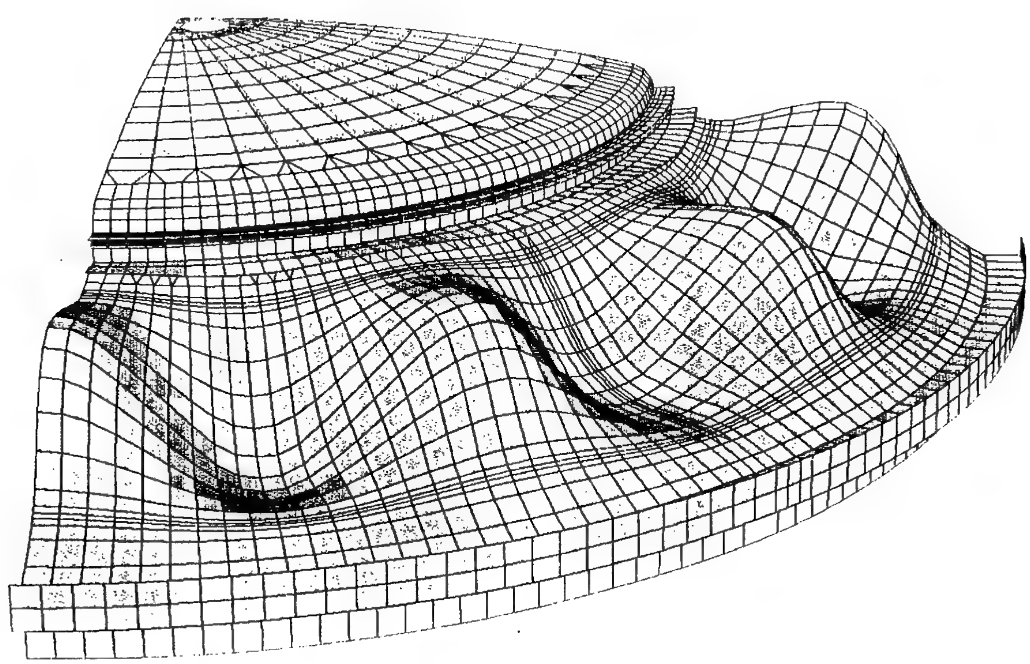


Fig. 6 Aft Cone Model (Buckling under external pressure)

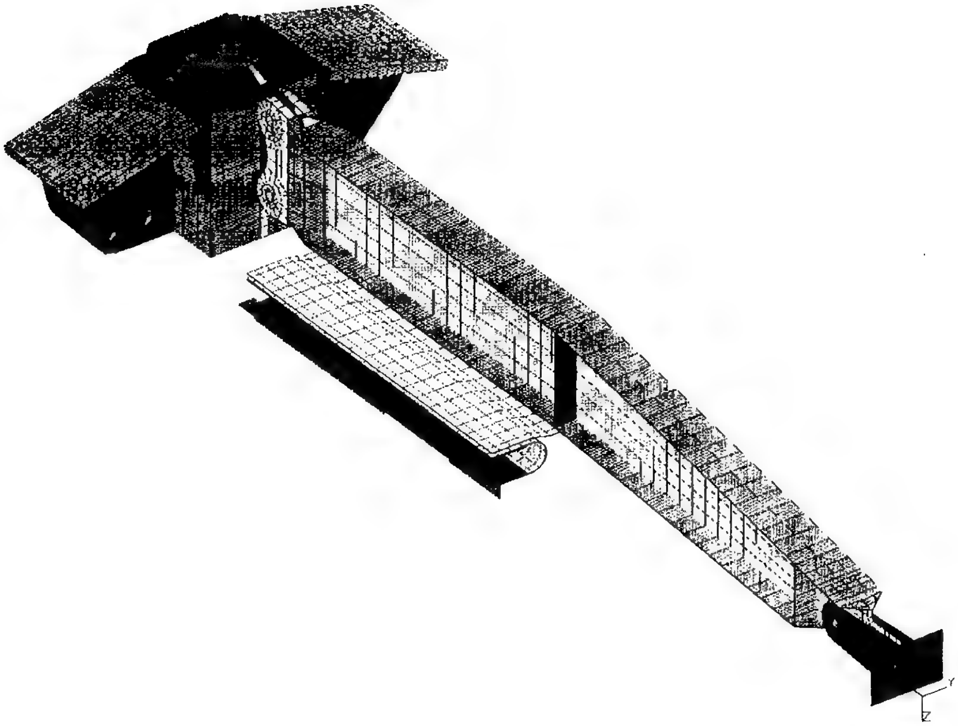


Fig. 7 Keel Fitting Model

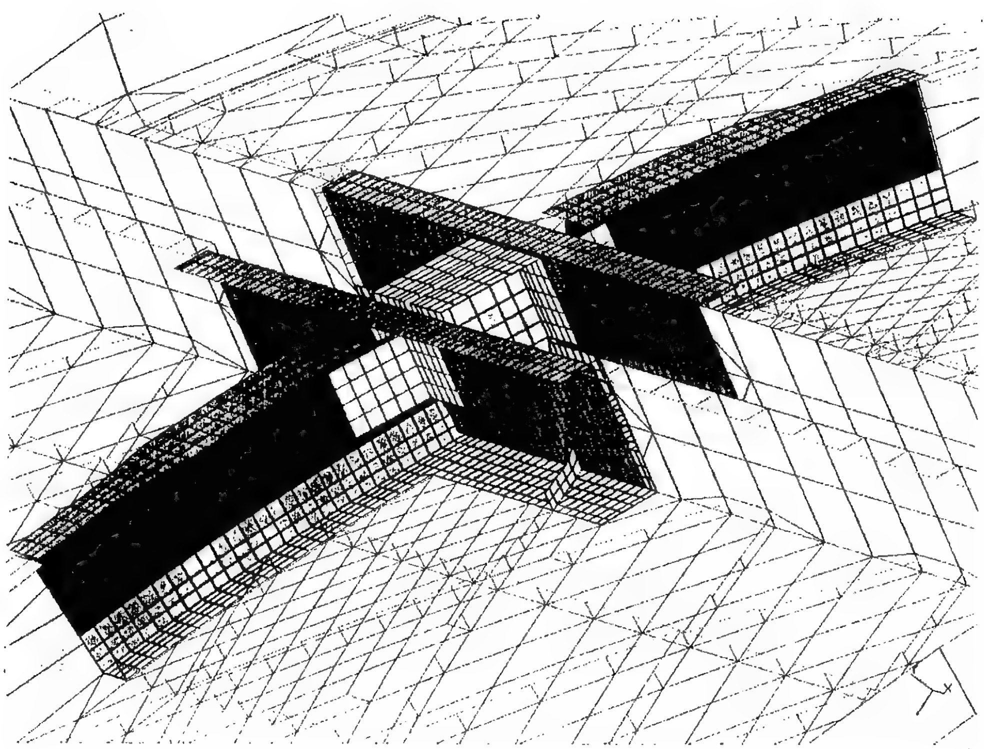


Fig. 8 Ring/Longeron Connection

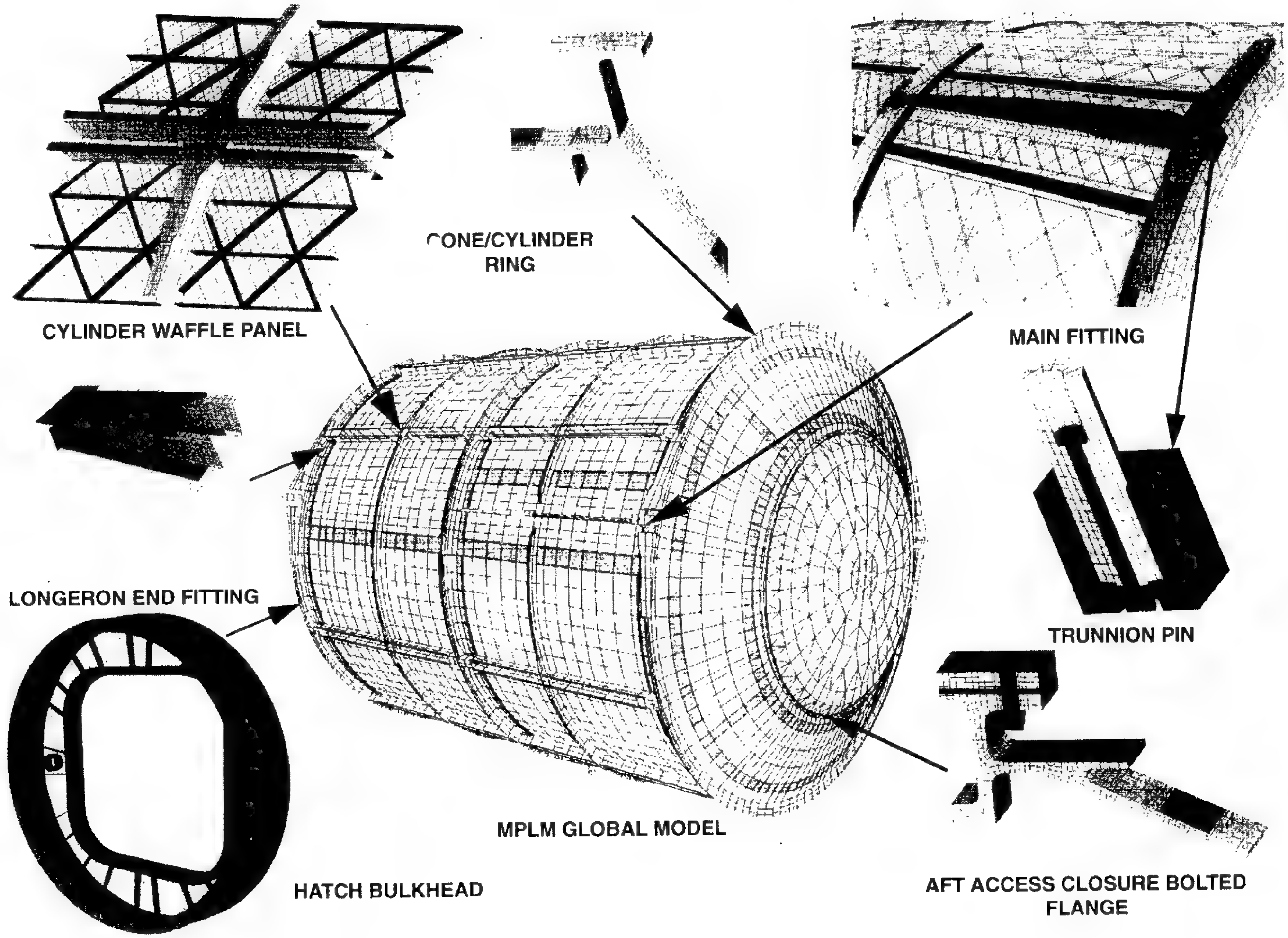
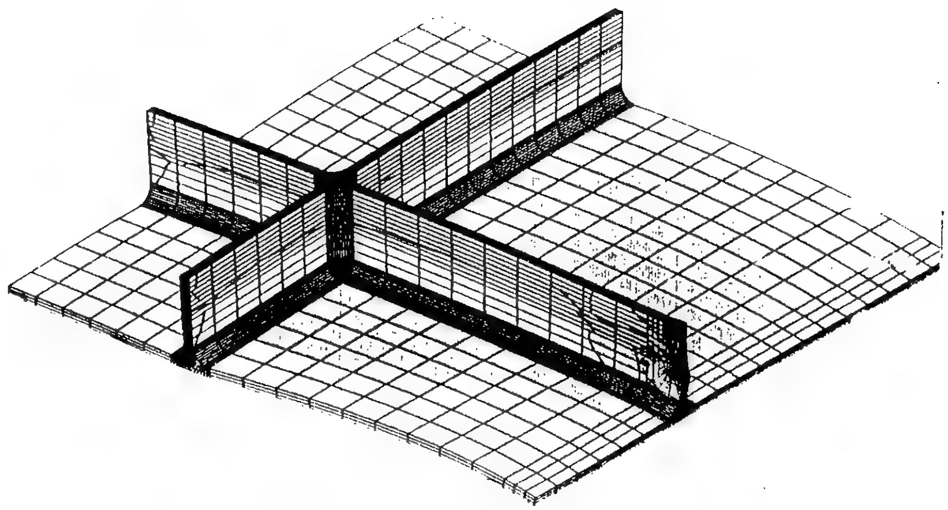


Fig. 9 MPLM Global and Local Models



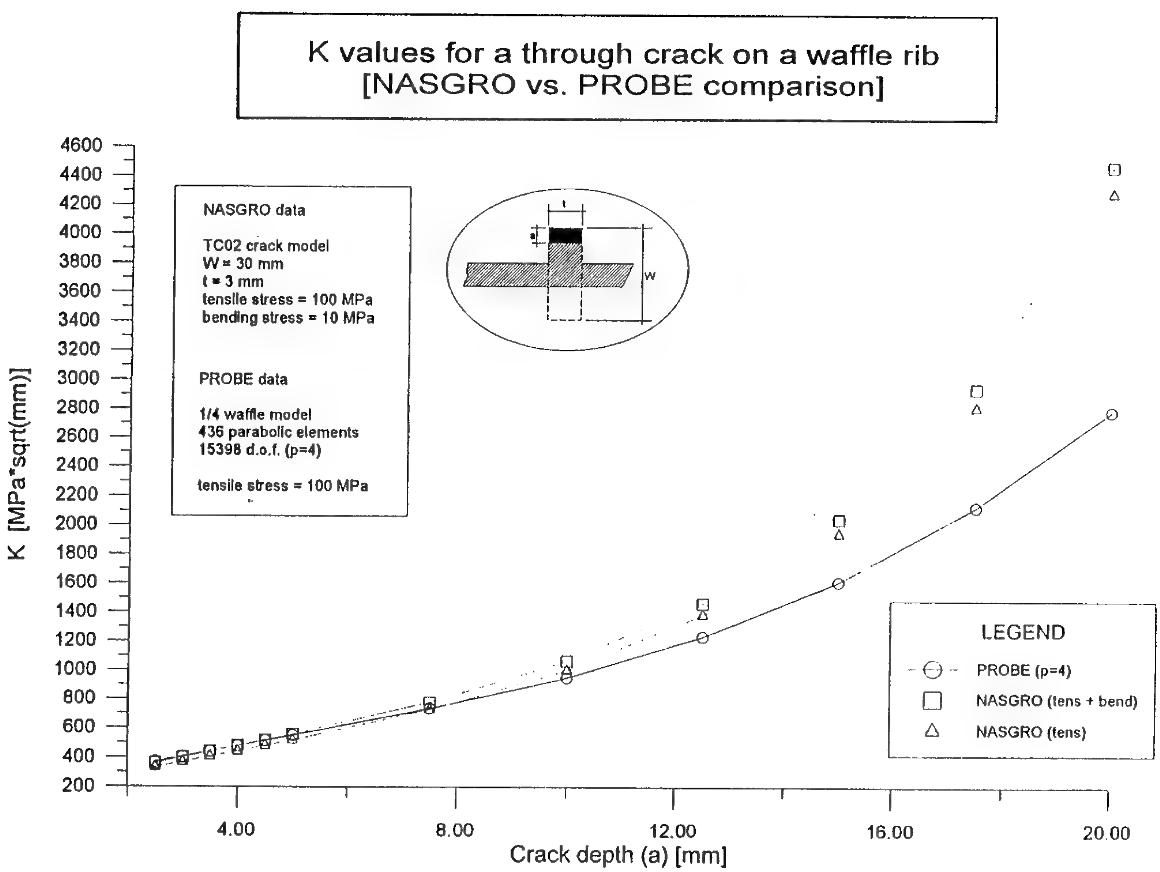
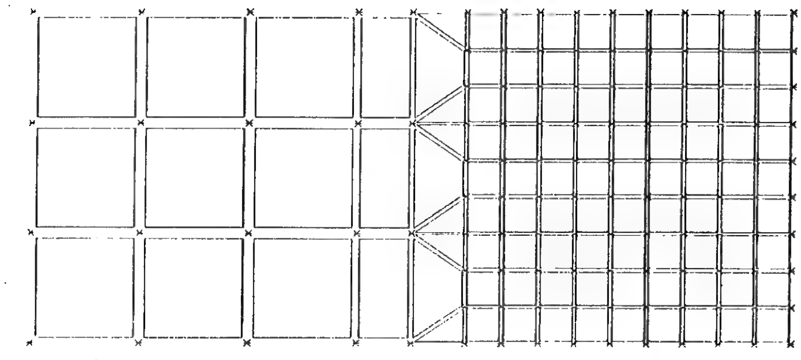
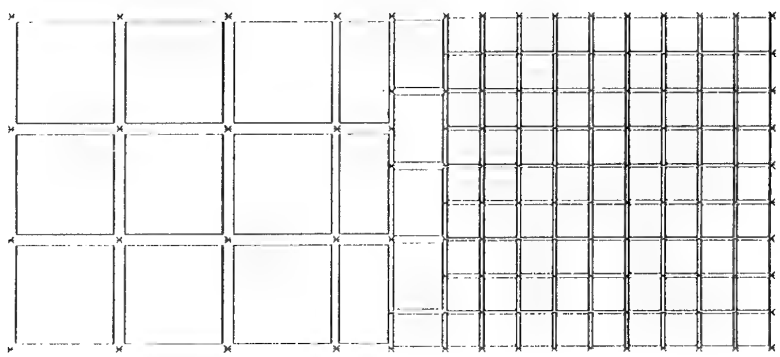


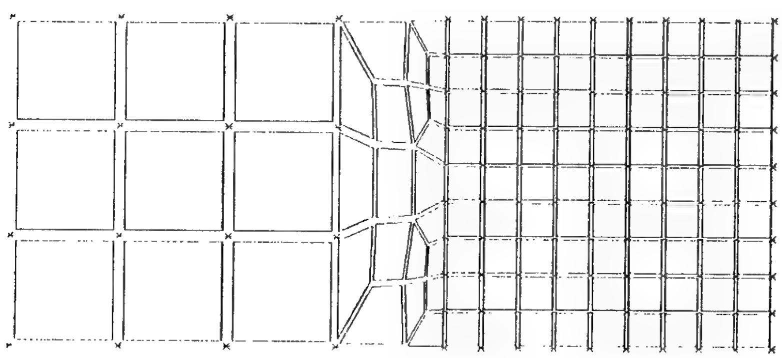
Fig. 10 Application of p-element to Fracture Mechanics



Using triangles



Using quadrilaterals with edge intermediate node



Using "free mesh"

Fig. 11 Mesh Transition

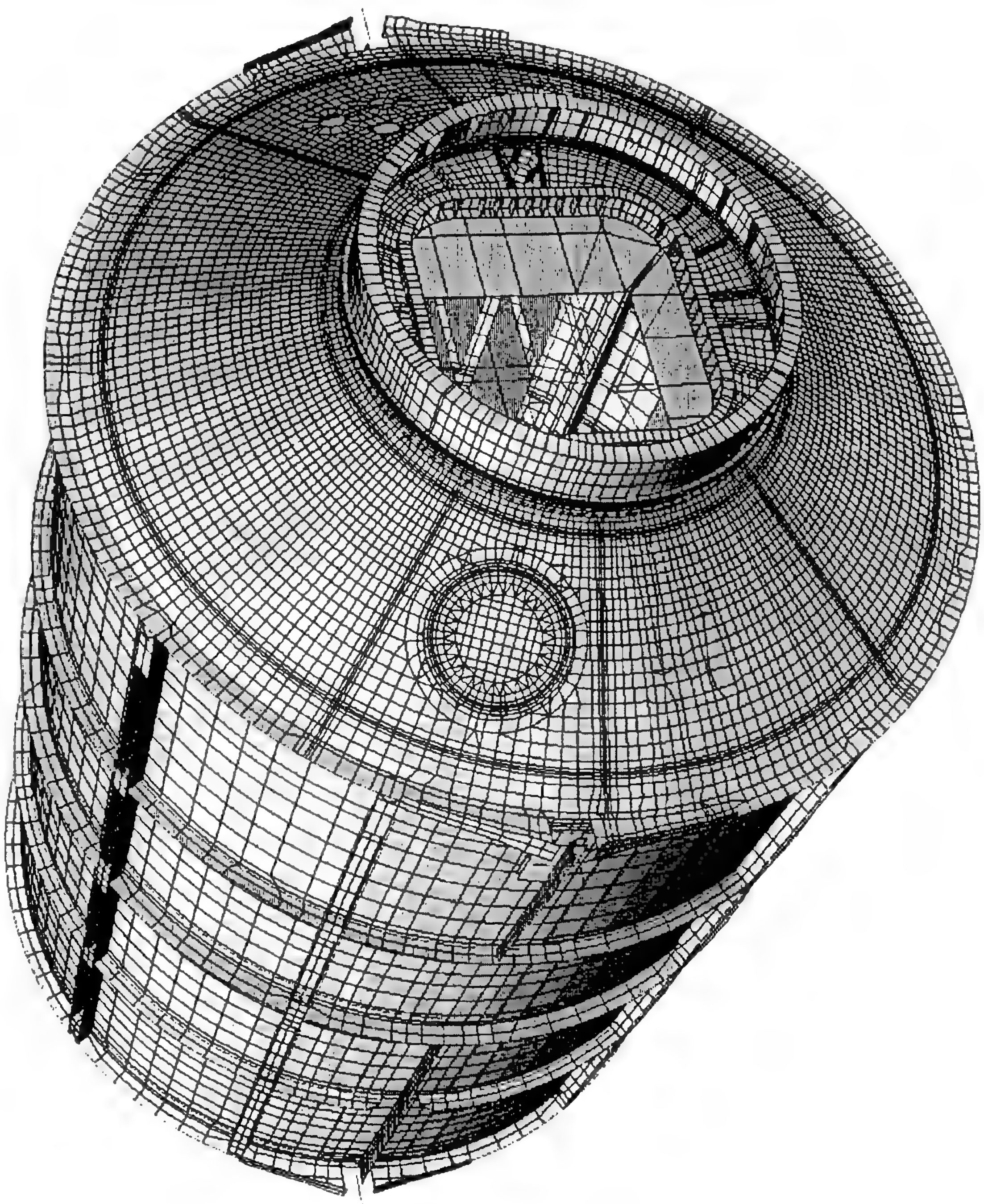


Fig. 12 The Forward Cone Detailed Model on the MPLM Global Model

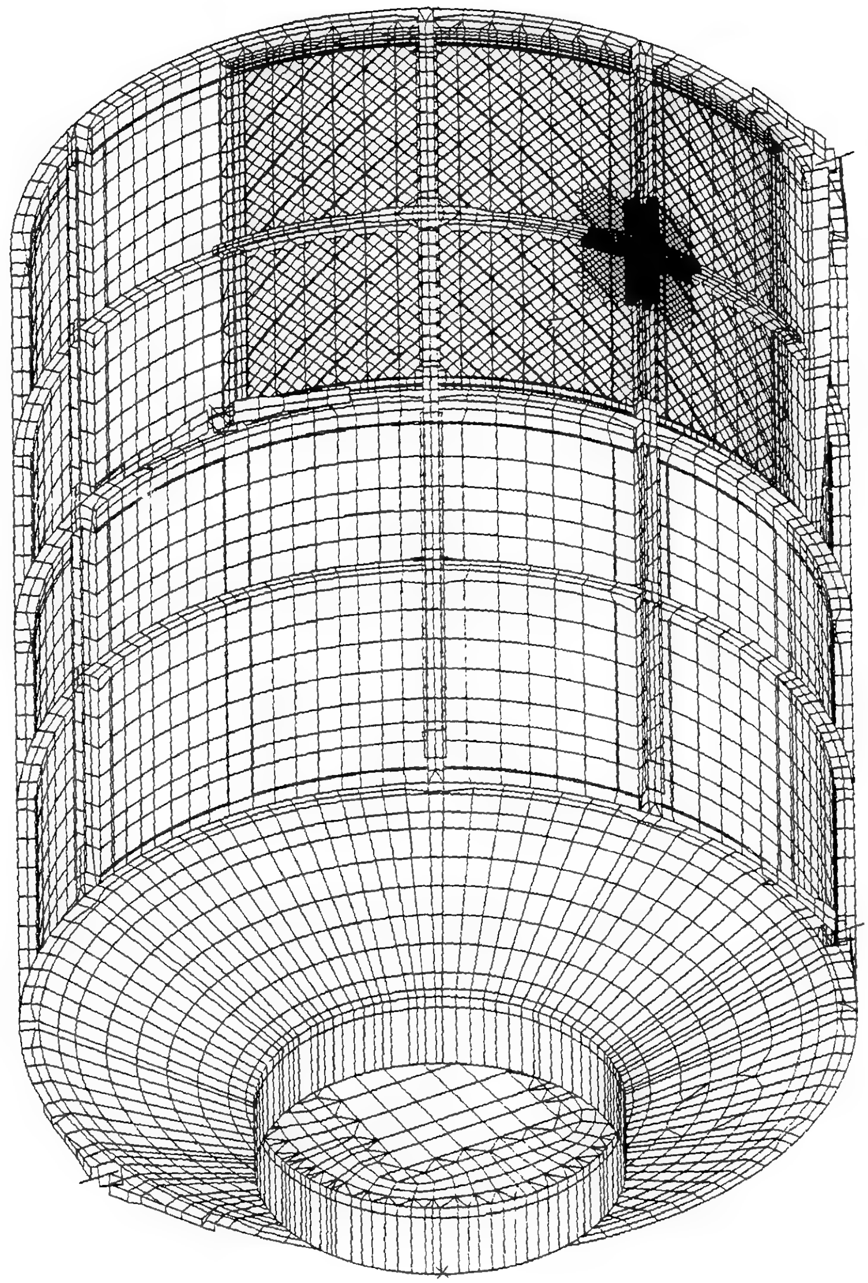


Fig. 13 The Longeron/Ring-Joint Detailed Model on the MPLM Global Model

TOPOLOGY OPTIMISATION OF 3D LINEAR ELASTIC STRUCTURES

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1. SUMMARY

In its most general form, the topology optimisation problem of structures can be viewed as the process of identifying the characteristic (indicator) function of the domain occupied by the optimal structure i.e.,

$$\chi = \begin{cases} 1 & \text{if material exists} \\ 0 & \text{if material doesn't exist.} \end{cases}$$

The topology design problem formulated above, is an integer programming problem (material /no-material) difficult to solve directly and may be ill posed. One of the methods used to overcome these difficulties is to relax the problem by introducing a material volume fraction parameter that has a continuous variation from zero to one. In engineering applications the relaxation is done introducing either a material model with microstructure, where the material properties are computed by the homogenisation method, or via an artificial, generally a polynomial, dependence between the mechanical properties and the material volume fraction .

Usually the obtained optimal (final) topologies using the material distribution approach do not characterise a well defined structure, i.e., it has regions with porous material and/or with checkerboard patterns. Also it has been observed that the final topology is not stable with the finite element mesh refinement. The goal of the *perimeter* constraint is to overcome these problems.

This work presents the development of a computational model for the topology optimisation of a three dimensional linear elastic structure using the material distribution approach. The optimisation criterion is the structural compliance, subjected to an isoperimetric constraint on volume and a constraint on structural *perimeter.*

The necessary conditions for optimum are derived analytically. These conditions are treated numerically through a suitable finite element discretization and solved by a first order method based on the optimisation problem Augmented Lagrangian. The computational model developed is tested and analysed in several numerical applications.

2. INTRODUCTION

Topology optimisation of structures is an area in optimisation of structures with specific design variables, the topological characteristics of the structure. Type of elements in a structure, number of members in a truss or frame, number and position of joints and number of holes are examples of this class of variables.

To formulate directly a problem that includes such a broad type and number of design variables is very difficult. To overcome this difficulty it was proposed (Kikuchi and Bendsøe[1]) to generalise the problem by the introduction of a material distribution model based on a porous material and assuming its material volume fraction as the design variable. Based on such a design variable, the concept behind the formulation is very simple, one can identify the structure with the regions where the volume fraction is one and holes with the regions where the volume fraction is zero.

However this apparent simplicity has a price. From the experience obtained in two dimensional applications, it has been observed that the optimal topologies do not characterise, in general, a well defined structure. They have regions with porous material and/or checkerboard patterns where it is difficult to identify the real structure. Also the final topology may change with the finite element discretization.

Recently Haber et al.[2] proposed, for the two dimensional case, a new approach to overcome these problems and to obtain manufacturable designs. This approach introduces two new design constraints. The first is based on the concept of perimeter and extends this concept to the material model for topology design where one has simultaneously solid, void and porous regions. The second constraint penalises intermediate volume fraction values. This additional constraints stabilise the final topology with respect to the finite element model.

This work is an application of this approach to the three dimensional case. It includes a constraint on the perimeter of the structure and since this constraint by itself does not avoid completely the porous material it is introduced a penalty on intermediate volume fraction values. The optimisation criterion is the structural compliance, subjected to an isoperimetric constraint on volume and a constraint on structural *perimeter.*

The necessary conditions for optimum are derived analytically. These conditions are treated numerically through a suitable finite element discretization and solved by a first order method based on the optimisation problem Augmented Lagrangian. The computational model developed is tested and analysed in several numerical applications.

3. THE OPTIMISATION PROBLEM

Consider a structural component, occupying the structural domain Ω , subjected to applied body forces $\mathbf{b}$ and boundary tractions $\mathbf{t}$ on Γ_t.

To introduce the material based formulation, consider the structural component made of a porous material with variable volume fraction μ. This material is simulated by a microstructure obtained by the periodic repetition of small prismatic holes (Figure 1). The optimisation goal is then to minimise, with respect to the material volume fraction and orientation, the compliance, equivalent to the energy norm of the total displacement, with an isoperimetric constraint on the total volume.

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In this case, the problem of topology optimisation can be stated as,

$$\min_{(0<\mu\leq 1,\theta_i)}\left(\int_\Omega b_i u_i d\Omega + \int_{\Gamma_t} t_i u_i d\Gamma\right) \tag{1}$$

subjected to the volume constraint,

$$\int_\Omega \mu \, d\Omega \leq \text{vol} \tag{2}$$

and where the displacement **u** is the solution of equilibrium equation, in virtual displacement form,

$$\begin{aligned}&\int_\Omega E^H_{ijkm}(\mu,\theta)e_{ij}(\mathbf{u})e_{km}(\mathbf{w}) - b_i w_i d\Omega - \\ &-\int_{\Gamma_t} t_i w_i d\Gamma = 0, \qquad \forall \mathbf{w} \text{ admissible}\end{aligned} \tag{3}$$

As mentioned previously, the final topologies obtained with this model are sometimes not well defined, and *checkerboard* patterns may appear. To overcame these difficulties it is introduced a set of new constraints. Haber et al.[2,3] proposes a control on perimeter for two dimensional problems and a penalization for intermediate volume fractions.

The perimeter of a structure is a measure of the boundary of the solid region $|\partial\Omega|$ thus penalising regions with checkerboard patterns. The material model used , where one may have subdomains with full material, no material and porous material, does not allow to compute the perimeter from the definition above, so one needs to assume a compatible perimeter measure.

To introduce this measure, let us consider the total variation of a piece wise continuous function in our case the material volume fraction μ,

$$\int_\Omega |\nabla\mu| \, d\Omega + \int_{\Gamma_J} |\langle\mu\rangle| \, d\Gamma. \tag{4}$$

In the previous expression, $<\mu>$ is the jump of the material volume fraction function and Γ_J is the respective discontinuity boundary (each finite element boundary in the case of our numerical model). Based on this variation, a possible measure for the perimeter is,

$$\begin{aligned}P(\mu) = &\int_\Omega \left[\left(\nabla\mu \bullet \nabla\mu + (\varepsilon/h)^2\right)^{1/2} - \varepsilon/h\right] d\Omega + \\ &+ \int_{\Gamma_J}\left[\left(\langle\mu\rangle^2 + \varepsilon^2\right)^{1/2} - \varepsilon\right] d\Gamma\end{aligned} \tag{5}$$

where ε is a positive small parameter that guarantees the differentiability of $P(\mu)$ and h is a characteristic dimension. It is easy to verify that this measure will recover the perimeter when the volume of porous material goes to zero, i.e., when the material volume fraction is only zero and one.

Based on this measure, we formulate the topology optimisation problem with perimeter control adding the constraint

$$P(\mu) - p = 0 \tag{6}$$

where p is the prescribed perimeter value.

For a complete description of this model in two dimensional applications see, e. g., Haber et al.[4].

Allaire and Kohn[5] and Bendsøe et al.[6] suggested that the non-optimal microstructures, such as prismatic voids used in this work, have a inherent penalty on intermediate volume fractions and consequently the structures obtained are structures with few zones of porous material. However, this implicit penalization is not exact and for example structures obtained with a unit cubic cell with cubic inclusions usually contain some volume of porous material. So, to obtain structures with only full material and voids, a penalty on intermediate volume fraction is used in this work.

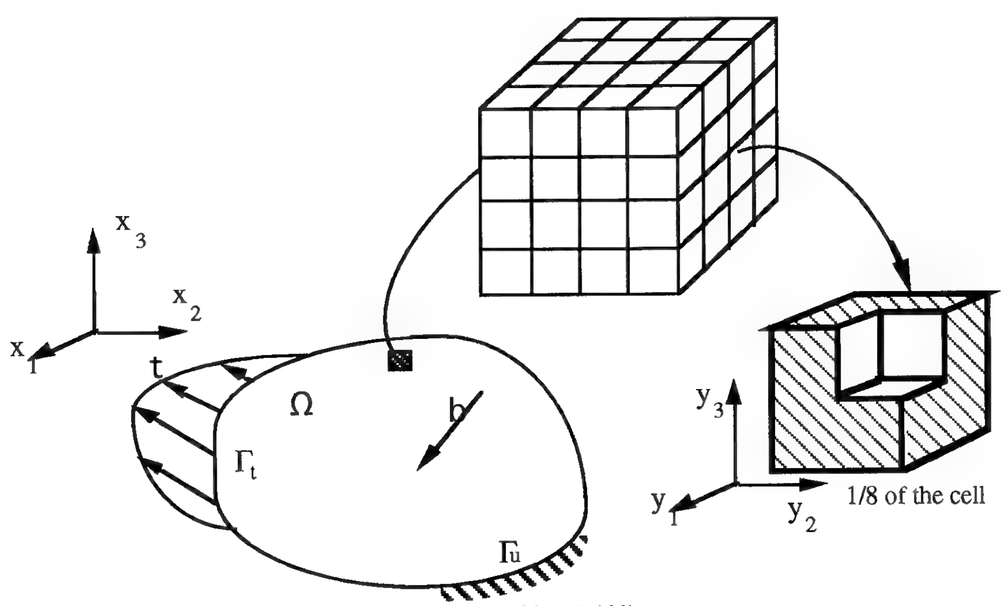


Figure 1. Load and Material Microstructure

This is done by adding to the objective function (1) the penalty term,

$$\alpha\int_{\Omega}\mu(1-\mu)\,d\Omega \tag{7}$$

that is non zero only for intermediate values of μ and where α is the penalty parameter.

Based on the considerations above, the optimisation problem with a constraint on perimeter and a penalty on intermediate volume fractions can be stated as,

$$\min_{(0\le\mu\le 1,\theta_i)}\left[\left(\int_{\Omega} b_i u_i\,d\Omega+\int_{\Gamma_t} t_i u_i\,d\Gamma\right)+ +\alpha\int_{\Omega}\mu(1-\mu)\,d\Omega\right] \tag{8}$$

subjected to the isoperimetric constraint on volume,

$$\int_{\Omega}\mu\,d\Omega\le \text{vol}, \tag{9}$$

and the constraint on perimeter,

$$P(\mu)=p \tag{10}$$

As seen previously the displacement **u** is the solution of the equilibrium problem (3).

4. POROUS MATERIAL EQUIVALENT ELASTIC PROPERTIES

For the porous material proposed, obtained by the periodic repetition of an unit cell with prismatic voids (see Figure 2), the asymptotic homogenisation method, relying on the microstructure local periodicity, is the natural model for the computation of the effective properties .

Assuming for the displacement $\mathbf{u}(\mathbf{x},\ \mathbf{x}/\varepsilon)$ an asymptotic expansion in terms of the cell size parameter ε, where $\mathbf{y}=\mathbf{x}/\varepsilon$, (see Figure 2),

$$\mathbf{u}^{\varepsilon}(\mathbf{x},\mathbf{y})=\mathbf{u}_0(\mathbf{x})+\varepsilon\mathbf{u}_1(\mathbf{x},\mathbf{y})+\varepsilon^2\mathbf{u}_2(\mathbf{x},\mathbf{y})+\ldots \tag{11}$$

the homogenised solution, obtained when limit $\varepsilon\to 0$, is $\mathbf{u}_0(\mathbf{x})$ (the first term of the asymptotic expansion) and is the solution of the equilibrium equation (3) with the porous periodic material substituted by an *equivalent* homogenised material.

In the case of homogeneous base material, the equivalent homogenised material properties are defined by,

$$E^H_{ijkm}=\mu\,E_{ijkm}-\int_{\yen}\left(E_{ijpq}\frac{\partial X^{km}_p}{\partial y_q}\right)dy \tag{12}$$

as a function of the volume fraction parameter $\mu=1-a_1a_2a_3=\int_{\yen}dy$ (see Figure 2). In the previous expresion the periodic functions $\mathbf{X}^{km}$ are solution of six equilibrium equations,

$$\int_{\yen}E_{ijpq}\frac{\partial X^{km}_p}{\partial y_q}\frac{\partial w_i}{\partial y_j}dy=\int_{\yen}E_{ijkm}\frac{\partial w_i}{\partial y_j}dy, \qquad \mathbf{X}^{km}-\text{Y}-\text{Periodic},\ \forall\mathbf{w}-\text{Y}-\text{Periodic} \tag{13}$$

defined on ¥, the unit cell subdomain occupied with homogeneous material (Figure 2).

The functions for the material properties $E^H_{ijkm}(\mu(\mathbf{a}))$ are obtained by a polynomial interpolation in the interval $a_i\in[0,1]$, i=1, 2, 3, with the values at interpolation points computed using the homogenisation code PREMAT (Guedes and Kikuchi[7]). On the other hand, the material properties also depend on the material orientation θ of the cells. This effect is taken into consideration by the rotation of homogenised material properties tensor, i.e., $\left(E^H_{ijkm}\right)_\theta=R_{in}R_{jo}R_{kp}R_{mq}E^H_{nopq}$ where $\mathbf{R}=\mathbf{R}(\theta)$ is the transformation tensor.

5. AUGMENTED LAGRANGIAN AND NECESSARY CONDITIONS

To obtain the necessary conditions for optimisation problem (8-10) in a form suitable for numerical approximation let us state the Augmented Lagrangian $L(\mathbf{u},\mathbf{v},\mathbf{a},\theta,\eta_1,\eta_2,\lambda,\gamma)$ associated with this problem as,

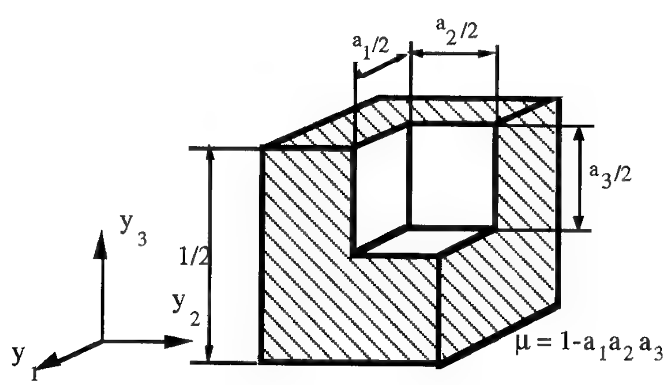


Figure 2 - 1/8 of the unit cell

$$\begin{aligned}L &= \int_\Omega \left[b_i u_i - E^H_{ijkm}(\mu,\theta) e_{km}(\mathbf{u}) e_{ij}(\mathbf{v}) + b_i v_i\right] d\Omega + \\ &+ \int_\Omega \left[\eta_1(\mu-1) - \eta_2 \mu\right] d\Omega + \\ &+ \frac{1}{2\rho}\left\{\left[\max\left(0, \lambda + \rho\left(\int_\Omega \mu d\Omega - \mathrm{vol}\right)\right)\right]^2 - \lambda^2\right\} + \\ &+ \frac{1}{2\beta}\left\{\left[\gamma + \beta(P(\mu) - p)\right]^2 - \gamma^2\right\} + \int_{\Gamma_t}(t_i u_i + t_i v_i) d\Gamma + \\ &+ \alpha \int_\Omega \mu(1-\mu)\, d\Omega\end{aligned} \tag{14}$$

where $\mathbf{v}, \eta_1, \eta_2, \lambda$ and γ are the Lagrange multipliers related with the equilibrium, bound, volume and perimeter constraints. These multipliers satisfy the set of conditions,

$$\begin{aligned}&\mathbf{v} = 0, && \text{on } \Gamma_u \\ &\eta_1(x) \geq 0, && \forall x \in \Omega \\ &\eta_2(x) \geq 0, && \forall x \in \Omega \\ &\lambda \geq 0, && \lambda \in \Re\end{aligned} \tag{15}$$

and $\rho > 0$ and $\beta > 0$ are the penalty factors for volume and perimeter constraints, respectively.

The set of necessary conditions are obtained directly from the stationarity of the Augmented Lagrangian (14) with respect to design variables, state variables and Lagrange multipliers respectively.

6. COMPUTATIONAL MODEL

The computational model developed to solve the topology optimisation problem uses the finite element method to compute the displacement field $\mathbf{u}$. Following this numerical method, the design domain is discretized by eight node isoparametric solid finite elements, and $\mathbf{u}^h$, the displacement field for the discrete problem, is the solution of the set of equilibrium equations,

$$\begin{aligned}&\int_\Omega E^H_{ijkm}(\mu,\theta) e_{ij}(\mathbf{u}^h) e_{km}(\mathbf{w}^h) d\Omega = \\ &= \int_\Omega b_i w_i^h d\Omega + \int_{\Gamma_t} t_i w_i^h d\Gamma \qquad \forall \mathbf{w}^h \text{ admissible}\end{aligned} \tag{16}$$

Based on the displacement finite element aproximation, the optimal material distribution is obtained from solution of the discrete version of the necessary conditions assuming μ (i.e., a the void dimensions) constant in each element.

Since μ is constant in each element one has $\nabla\mu = 0$ and the perimeter is defined as,

$$P(\mu) = \int_{\Gamma_j}\left[\left(\langle\mu\rangle^2 + \varepsilon^2\right)^{1/2} - \varepsilon\right] d\Gamma. \tag{17}$$

In this case the stationarity condition with respect to μ is,

$$\begin{aligned}&\int_{\Omega_e} -\frac{\partial E^H_{ijkm}}{\partial \mu} e_{km}(\mathbf{u}^h) e_{ij}(\mathbf{u}^h) d\Omega_e + \\ &+ \max\left[0, \lambda + \rho\left(\int_{\Omega_e} \mu\, d\Omega - \mathrm{vol}\right)\right] \int_{\Omega_e} d\Omega_e + \\ &+ \left[\gamma + \beta(P(\mu) - p)\right] \int_{\Gamma_e} \frac{\langle\mu\rangle}{\left(\langle\mu\rangle^2 + \varepsilon^2\right)^{1/2}} d\Gamma_e + \\ &+ \alpha \int_{\Omega_e}(1-2\mu) d\Omega_e + \int_{\Omega_e} \eta_1 - \eta_2 d\Omega_e = 0, \quad \text{on } \Omega_e.\end{aligned} \tag{18}$$

In the previous stationarity condition, Ω_e is the element domain, Γ_e is the element boundary, μ is the volume fraction and $e_{ij}(\mathbf{u}^h)$ is the strain tensor .

Equation (18) is solved iteratively using the following algorithm, based on a first order augmented Lagrangian method, to obtain the optimal volume fraction μ in each element,

$$\mu_{k+1} = \begin{cases} \max[(1-\zeta)\mu_k, 0] & \text{if } \mu_k + sD_k \leq \max[(1-\zeta)\mu_k, 0] \\ \mu_k + sD_k & \text{if } \max[(1-\zeta)\mu_k, 0] \leq \mu_k + sD_k \leq \min[(1+\zeta)\mu_k, 1] \\ \min[(1+\zeta)\mu_k, 1] & \text{if } \min[(1+\zeta)\mu_k, 1] \leq \mu_k + sD_k \end{cases} \tag{19}$$

In the previous recursive formula, $\mathbf{D}_k$ is a descent direction at iteration k and its components are given as,

$$\begin{aligned}D_k &= \int_{\Omega_e} \frac{\partial E^H_{ijkm}}{\partial \mu_k} e_{km}(\mathbf{u}^h) e_{ij}(\mathbf{u}^h) d\Omega_e - \\ &- \max\left[0, \lambda_k + \rho\left(\int_{\Omega_e} \mu_k\, d\Omega - \mathrm{vol}\right)\right] \int_{\Omega_e} d\Omega_e - \\ &- \left[\gamma_k + \beta(P(\mu_k) - p)\right] \int_{\Gamma_e} \frac{\langle\mu_k\rangle}{\left(\langle\mu_k\rangle^2 + \varepsilon^2\right)^{1/2}} d\Gamma_e - \\ &- \alpha \int_{\Omega_e}(1-2\mu_k) d\Omega_e\end{aligned} \tag{20}$$

The step length factor s is a positive number constant through the iterative process, $\zeta>0$ defines the active upper and lower bound constraints and ρ, β and α are the penalty factors associated with the volume, perimeter and intermediate volume fraction constraints respectively. All these parameters are chosen by the user.

The Lagrange multipliers related with the volume and perimeter constraints are updated from the stationarity conditions with respect to λ and γ i.e.,

$$\lambda_{k+1} = \max\left[0, \lambda_k + \rho\left(\int_\Omega \mu_k\, d\Omega - \mathrm{vol}\right)\right] \tag{21}$$

$$\gamma_{k+1} = \left[\gamma_k + \beta(P(\mu_k) - p)\right] \tag{22}$$

Finally the optimal material orientation is computed solving analytically the optimal condition obtained from the

stationarity of Lagrangian with respect to θ_i. For the three dimensional problem the solution is proposed by Rovati e Taliercio[8] and for particular case of cubic material the optimal solution is satisfied when the directions of orthotropy are collinear with the directions of principal stress/strain.

In short, the numerical process consist on defining for each element the homogenised elastic coefficients for a initial value of μ and θ, then one calculates the displacement field $\mathbf{u}^h$ due to the applied loading (16). Based on these values the necessary optimality condition (18) is checked, if verified the process stops if not a new values for μ θ, λ and γ are computed (19, 21, 22) and the process restarts. The flow diagram of the process is presented in the figure 3

7. EXAMPLES

To test the model, two numerical examples were solved: A three dimensional (3D) beam and a 3D plate with concentrated load . The two dimensional versions of these examples are often used in the topology optimisation literature and are known as the MBB beam example and Bicycle wheel example[3].

In Figure 4 it is shown the geometry, the loading conditions, and the boundary conditions for these two examples. On the 3D beam the light grey area is the design area and the darker area is considered fixed through the optimisation procedure. The thickness of the fixed material, the load and the represented boundary conditions are uniform through the depth. The finite element discretization uses 1500 and 1920 8-node (brick) elements for the beam and plate respectively, and the design variables are constant within each finite element. In these examples, the total applied force is P= 1800 |F| and it is assumed that the unit cell material is isotropic (see Figure 2), with Young's Modulus equal to $2.1*10^6$ (|F| L^{-2}) and Poisson constant equal to 0.3.

7.1 3D Beam

For this example the volume constraint is 40% of the total design volume (Vol. Constr. = 3.6864 (L^3)), and four cases were tested: 1 - no perimeter control, no penalization on intermediate densities, 2 - target perimeter p =28 (L^2), penalization , 3 - target perimeter p =35 (L^2), penalization and 4 - target perimeter p =40(L^2), penalization.

Figures 5 show, for all the cases the volume fraction distribution at the final design where elements with $\mu < 0.1$ were not printed.

The numerical results are summarised in Table 1. Note that C stands for compliance, the subscripts *i* and *f* for initial and final respectively, and $\|\mathbf{D}\|$ for the norm optimality condition (18).

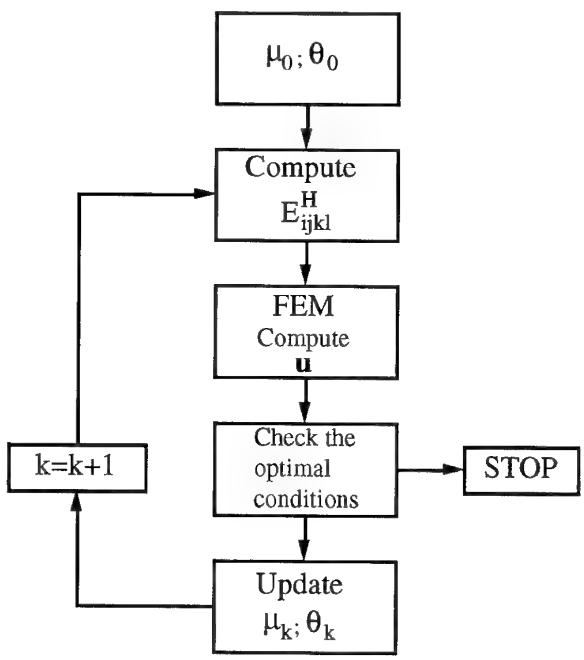
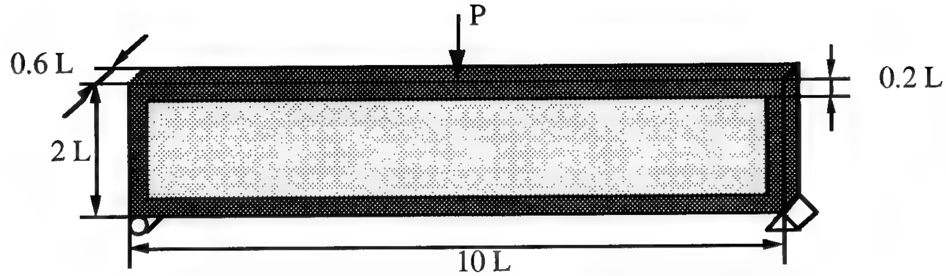
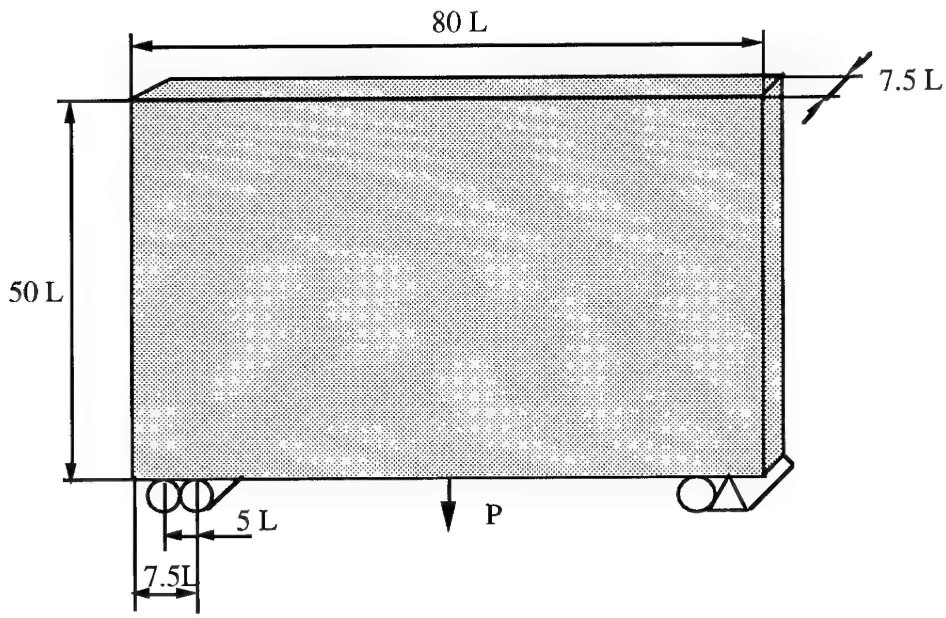


Figure 3 - Numerical model flow diagram



a) 3D beam



b) 3D plate

Figure 4 - Geometry, loading and boundary conditions

Table 1: Numerical results for the 3D beam example

case	C_i(lFlL)	target p (L^2)	$\|\mathbf{D}\|_i$	C_f	p_f (L^2)	vol_f (L^3)	$\|\mathbf{D}\|_f$
1	91.19	-	12.703	65.88	-	3.705	0.613
2	91.19	28	9.342	74.33	27.20	3.707	0.359
3	91.19	35	10.081	72.20	35.09	3.702	1.59
4	91.19	40	9.229	75.62	40.66	3.632	0.078

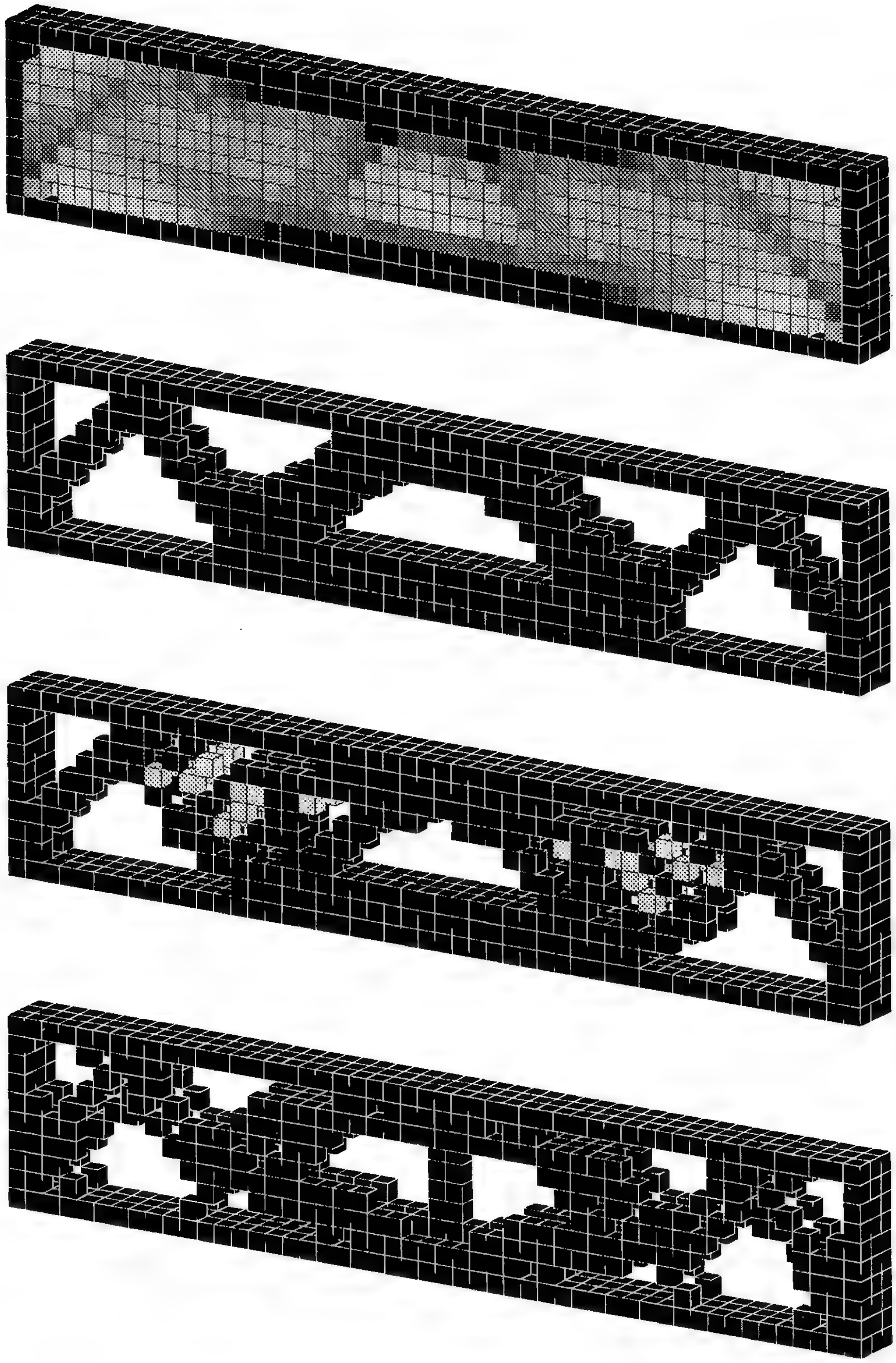


Figure 5 - Volume Fraction Distribution for 3D beam ($\mu \geq 0.1$).
Top to Bottom cases 1 to 4.

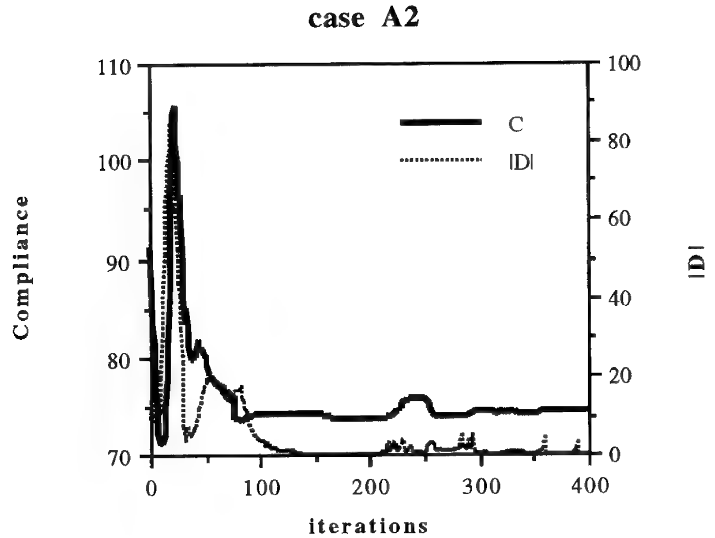


Figure 6 - Convergence history for compliance and norm of gradient - case A2

The numerical results obtained show a fair reduction of the compliance, with small violation of the perimeter and volume constraints. Moreover, the gradient of the objective function is reduced considerably from its initial value.

The obtained topologies, as shown in figures 5 have similarities with some of the results obtained for two dimensional problems by Haber et al.[2,3,4]. It is observed a significant dependency of the final design and compliance on the perimeter constraint. Also it should be remarked that a careful choice of optimisation parameters is necessary in order to obtain reasonable results, and the algorithm is very sensitive to small changes in these parameters.
The iteration history is shown in figures 6 for case 2.

7.2 3D Plate
For this example the volume constraint is 25% of the total design volume (Vol. Constr. = 7500 L^3) and three cases are considered: 1- without perimeter constraint and without penalization on intermediate densities, 2- without perimeter constraint but with penalty on densities and 3-with perimeter constraint and penalty on densities.

For case 3 of this example the initial design is the optimal topology obtained by the case 2, instead of an uniform volume fraction distribution. The reason for this procedure is, once more, the difficulty to guess the right optimisation parameters, in order to obtain a final topology which satisfies the constraints when one starts with uniform design. So, the perimeter constraint was introduced after a penalised design had been obtained.

The optimal distribution of volume fraction, for all cases, is shown in figure 7 where elements with $\mu<0.1$ were not printed, and the table 2 shows the numerical values for these cases.

The results show the effect of penalization on intermediate densities, and the effect of perimeter to control the number of the holes in a structure.

Table 2: Numerical results for the 3D plate

case	C_i(|F|L)	target p (L^2)	$\|\|D\|\|_i$	C_f	p_f (L^2)	vol_f (L^3)	$\|\|D\|\|_f$
1	3.38	-	4.794	1.10	932	7500	1.12×10^{-2}
2	3.38	-	4.727	1.32	3632	7500	6.07×10^{-3}
3	1.32	2800	3.189	1.49	2815	7415	3.25×10^{-1}

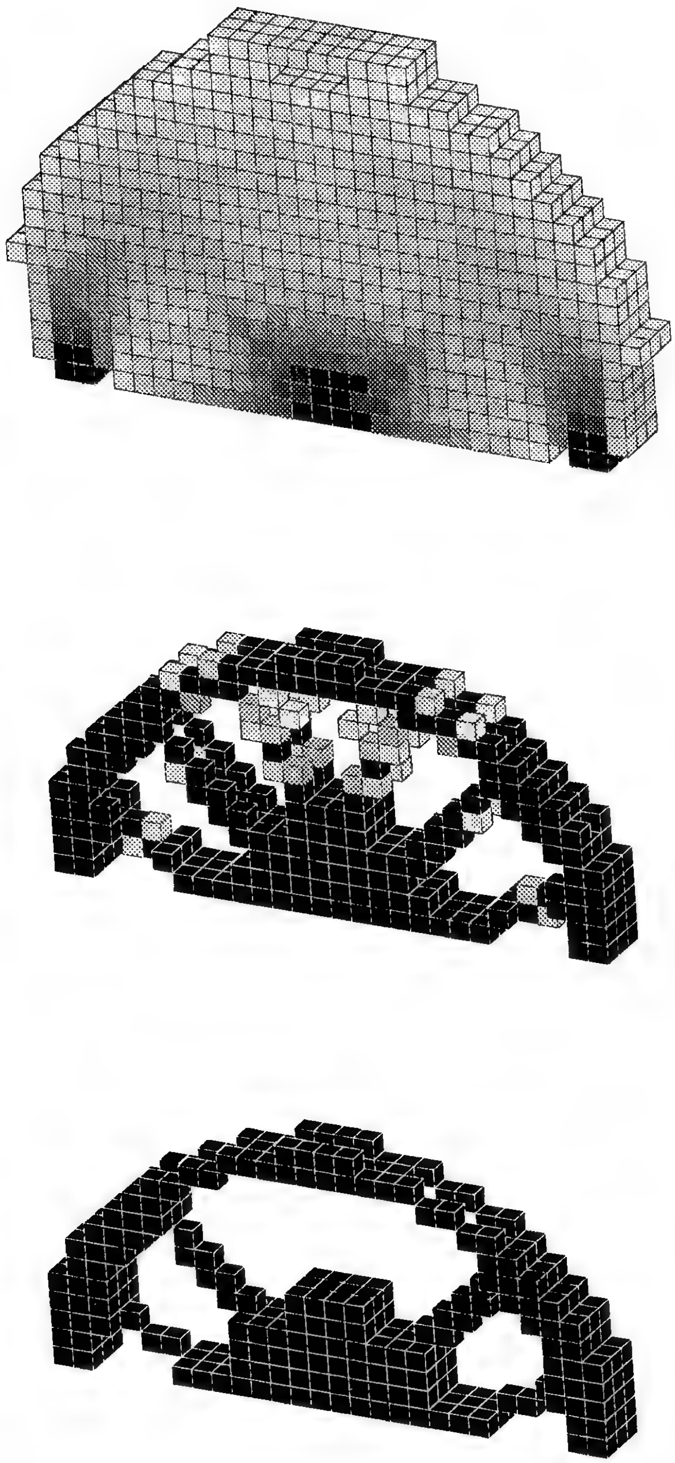


Figure 7 - Volume Fraction Distribution for bicycle wheel ($\mu\varsigma 0.1$).
Top to Bottom cases 1 to 3.

6. CONCLUSIONS

In this paper a computational model for a topology optimisation method for three dimensional linear elasticity with control on perimeter was presented.

In spite of using a sub-optimal microstructure obtained by cubic cells with holes, the resultant topology, without perimeter control and penalization on intermediate densities, has many regions with porous material. The results show that the model developed in this work provides topologies which presented a very small amount of porous material since the control on perimeter and the penalization on intermediate densities are considered. These topologies, satisfying the perimeter and volume constraints, allow for a better identification of the final three dimensional structure.

The method seems to provide an efficient tool to predict topology of structures, however to become a practical design tool still more work is needed because of the computational time involved and the required computer resources. One of the issues that still needs careful study is the choice of the optimisation algorithm parameters. It was observed that the method is very sensitive to the penalty factors and this fact influences significantly the final results. The 3D plate presented above is an example of this fact.

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14. Abstract

Integrated airframe design embraces the concept of bringing together all of the aspects of airframe design, including various disciplines such as structures, materials, aerodynamics, propulsion, systems, controls and manufacturing from conceptual design all the way through to the final product and its repair and maintenance.

The results of this AGARD Workshop on Integrated Airframe Design emphasized that the recent and future advances in high-performance computer hardware and software systems provide the opportunity to create a process that will allow these disciplines to rapidly interact with one another.

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